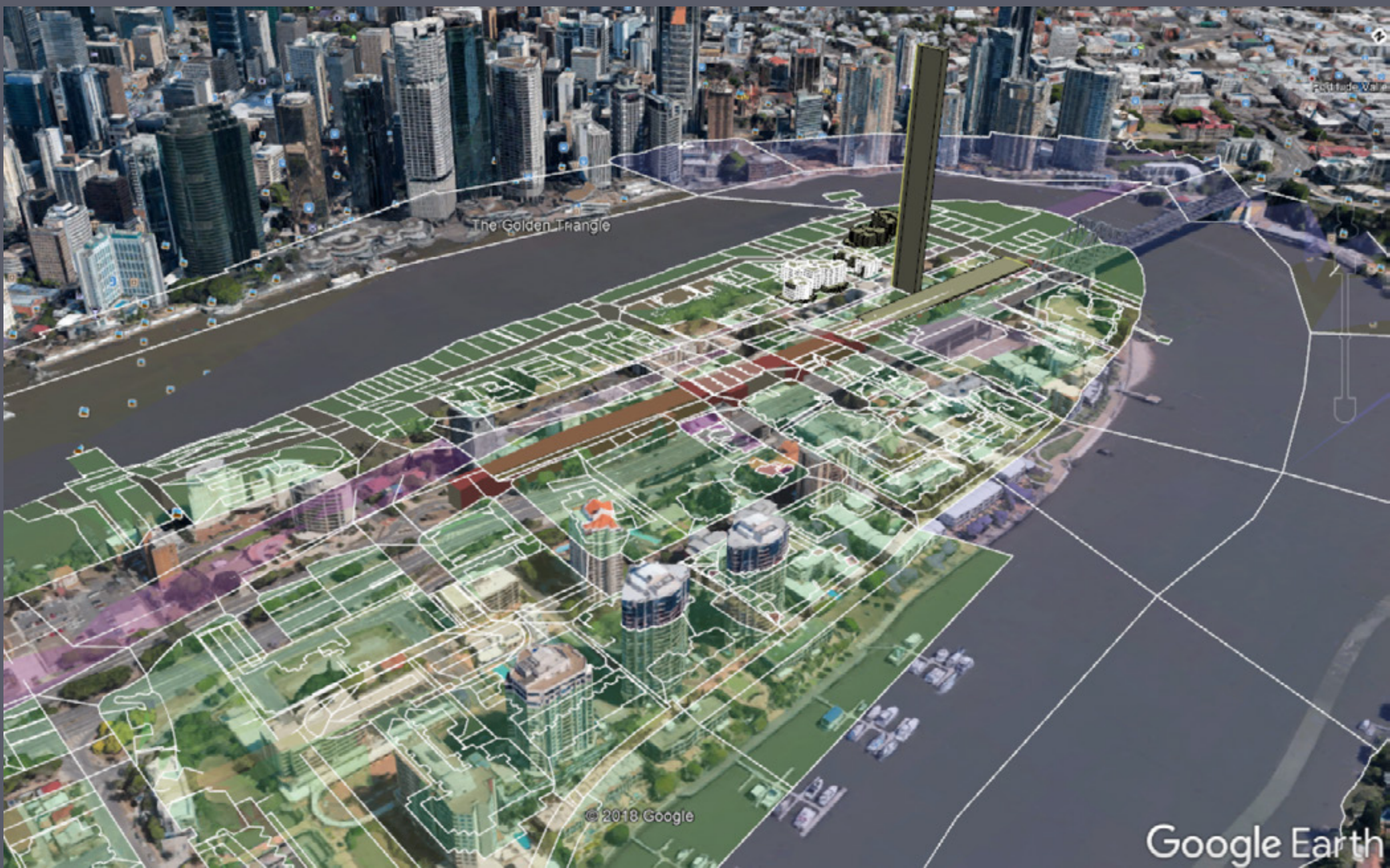
FIG publication

Best Practices 3D Cadastres

Extended version



Editor: Peter van Oosterom

The front and the back cover illustrations show screenshots of the prototype of a web-based 3D Cadastre dissemination system built on top of Google Earth. The cadastral parcels are elevated 50 meters in order to visualize the relationship with the topography. The 2D parcels (from the DCDB) are draped over a terrain elevation model, the building format Survey Plans are converted into 3D parcels (property units in building), the volumetric format Survey Plans are also converted 3D parcels and correspond to various types of objects: below (tunnel parts), above (property under ramp to bridge), and through the earth surface (air shaft).

***Front cover:** looking from the South-East towards Kangaroo point (Brisbane, Queensland), note the correspondences between the cadastral objects and the topographic objects, 50 meters below.*
***Back cover:** looking from the North-West towards Kangaroo point, note the reddish volumetric parcels (tunnel parts) bellow the semi-transparent greenish surface parcel, a bit further inland many greyish 3D parcels from building format Survey Plans (some with black, some with white edges).*

Queensland Digital Cadastral Database (DCDB) data and Survey Plan data provided by Sudarshan Karki (Queensland Government, Department of Natural Resources, Mines and Water), the terrain elevation model provided by Martin Kodde (Fugro) / Glen Ross-Sampson (Roames), conversion from building format and volumetric format Survey Plans, and draping of 2D parcels over terrain elevation model by Rod Thompson (in the context of the on-going 3D Cadastral visualization project with Peter van Barbara Cemellini and Marian de Vries, TU Delft).

FIG publication

BEST PRACTICES 3D CADASTRES

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CONTENT

PREFACE

Over the last 15 years or so, a number of political, economic, environmental and social factors as well as the rapid technological innovation have profoundly changed the outlook for good management of land, the sea and especially the built environment. In this context, the issue of security of tenure and registration of property rights is recognized as an increasingly important component for eliminating poverty and achieving sustainable development of land, real estate and property markets in all UN member states, particularly in urban areas.

In view of the Sustainable Development Agenda 2030 all UN member states are developing and modernizing their cadastre and land registration systems and in parallel formalizing their property markets. Present land administration systems and cadastres need re-engineering; they must continually evolve to cope with the ongoing megatrends, such as urbanization, demographic change, societal disparities, the digital transformation, volatile global economy, anthropogenic environmental damage and so on.

Much of the current research by the surveying profession in this field focuses on issues related to 3D geo-information, tools for data collection, cloud solutions, data management, optimizing processes and web-based information dissemination; standardization of 3D information, advanced modelling and visualization, as well as formalizing and building sustainable real estate markets as a pillar for robust economic urban growth; and related policies, legal and institutional aspects and knowledge sharing in operational experiences, the emerging challenges and the good practices. The significance of these areas of interest for the good management of land, the sea and especially the built environment is well understood.

It is mainly about people and their living in urban settlements. It is mainly about developing the "cities we want", digitally networked and intelligent. And we, as geo-information professionals, vendors, providers, managers, professionals as well as academics and researchers, are expected to develop services and tools to deliver administrative, economic and social benefits. Our colleagues, representatives of business, academia and public administration; managers of geodata from all over the world; young entrepreneurs and creative minds; all are working toward the same goal, trying to increase the "value" of geodata for the people. They do so in order to get more benefit, more transparency, more safety, more environmental quality, more growth, more fairness, more efficiency in governance of urban areas, more smart cities.

No reality has a more direct bearing on the subject of 3 dimensional geo-information and cadaster than the growth of large cities, especially in the developing countries of the world, and especially in the phenomenon of the mega cities. For our young readers let me give some impressive information. A mega city is an urban area of 10 million population or more. The Economist "Pocket World in Figures" 2016 Edition, lists thirty-three mega cities of the world from Bangalore, India at ten point one million, thirty-third on the list, to number one Tokyo at thirty-eight million.

The World Health Organization (WHO) has reported that in 2014 fifty-four percent of the world's people lived in urban areas, up from thirty-four percent in 1960. The tipping point, according to most authorities, occurred in 2007 when there were more urban dwellers than rural residents in the world: the so-called "urban millennium."

The United Nations predict that by 2050 sixty-six percent of the world's population will live in urban areas.

Much is being written about the growth of urban populations and the concurrent growth of urban infrastructures and institutions to support this huge growth of two-thirds of the world's people in the cities. Of all the institutions that must be developed to anticipate, keep abreast of and support this growth, the cadaster stands foremost in the interest of commerce, real estate investment, municipal revenue, and personal property security, not to mention urban planning and management.
As the cities grow they grow vertically as well as horizontally thereby introducing the element of the third dimension.
Recent innovative thinking has introduced the concept of a multi-dimensional multi-purpose land information system. It is a logical extension of the 3D cadaster concept, by adding the time dimension and the detail/scale dimension to the equation.
In a discussion of "cost effectiveness" one must consider time, that 4th dimension that we speak of. In time, we are usually referring to land titles history and time-sharing rights, or how the shape and size of land parcels and cadastral objects change over time, but it is also a matter of time-cost in the construction of the cadaster, as well as the time/property value relationship. As the great cities of the world become mega, the value of land and its improvements grow as well. Thus the time/value relationship and its impact on land administration and the need for continuing research on fundamental policy issues of technical administrative, legal and financial aspects of land administration.
This publication is a further contribution of FIG in this on-going process of improving land administration systems. It responds to the need for international research in building effective land administration infrastructures with modern information technology that will support the 2030 global policy goals for sustainable development. This study takes into account the recent developments that have taken place, and I hope that it will lead to a better understanding of the concept of a 3D cadaster.

Prof Chryssy A Potsiou
President of FIG

ORGANIZATION OF THE WORKING GROUP ON 3D CADASTRES

The website of the Working Group (WG) can be found at http://www.gdmc.nl/3DCadastres/. This website contains the scope description of the WG, workshops, conducted questionnaires, literature, members, etc. Peter van Oosterom is the current WG chair (term 2014-2018).

Members of the FIG joint commission 3 and 7 Working Group on 3D Cadastres

Argentina	Diego Alfonso Erba
Australia	Ali Aien, Don Grant, Mohsen Kalantari, Sudarshan Karki, Davood Shojaei, Rod Thompson
Austria	Gerhard Muggenhuber, Gerhard Navratil
Bahrain	Neeraj Dixit, Ammar Rashid Kashram
Brazil	Andréa Flávia Tenório Carneiro
Canada	Francois Brochu, Louis-André Desbiens, Paul Egesborg, Marc Gervais, Jacynthe Pouliot, Francis Roy
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Switzerland	Helena Aström Boss, Robert Balanche, Laurent Niggeler
Trinidad and Tobago	Charisse Griffith-Charles
Turkey	Cemal Biyik, Osman Demir, Fatih Döner
United Kingdom	Gareth Robson, Carsten Rönsdorf
USA	Bod Ader, David Cowen, Carl Reed, Alex Smith

INTRODUCTION

At the end of the two most recent 4-year terms (2010-2014 and 2014-2018) of the joint commission 3 'Spatial Information Management' and commission 7 'Cadastre and Land Management' FIG Working Group on 3D Cadastres, it was decided to collect the best known practices in a single FIG publication. Key authors were invited to lead a chapter on one of the following topics:

- Chapter 1. Legal foundations (Dimitrios Kitsakis),
- Chapter 2. Initial Registration of 3D Parcels (Efi Dimopoulou),
- Chapter 3. 3D Cadastral Information Modelling (Peter van Oosterom),
- Chapter 4. 3D Spatial DBMS for 3D Cadastres (Karel Janečka), and
- Chapter 5. Visualization and New Opportunities (Jacynthe Pouliot).

The mentioned lead authors have each teamed-up with a group of authors to produce their chapters. A lot of inspiration was found in the earlier 3D Cadastres activities of FIG, such as the various 3D Cadastres workshops, the two 3D Cadastres questionnaires, and the presentations and publications at the 3D Cadastres sessions at every FIG Working Week and Congress. The result is a quite extensive FIG publication of about 250 pages, which has been language checked by native English speakers.

Based on this long version also a shorter version of about 80 pages is produced. The short version will become available as FIG publication both in hard-copy (paper) and soft-copy (pdf online). The long version will only be published in soft-copy form and in the style of the FIG proceedings.

Both versions are expected to be available at the FIG congress 2018 in Istanbul, Turkey. Every chapter will be shortly introduced by one of the authors at the FIG congress 2018.

1. HISTORIC BACKGROUND

The FIG publication '3D Cadastres Best Practices' has quite a long history. Many 3D Cadastral activities have been conducted during the past two decades: five FIG 3D Cadastres workshops, sessions at FIG working weeks and congresses, three special issues in international scientific journals, several 4-year terms (2004-2008, 2010-2014 and 2014-2018) of the joint commission 3 and commission 7 FIG Working Group on 3D Cadastres, and two questionnaires (2010 and 2014). Below an overview of the workshops organized so far, which are all published in FIG proceedings:

- International FIG Workshop on 3D Cadastres, 28-30 November 2001, Delft, The Netherlands;
- 2nd International Workshop on 3D Cadastres, 16-18 November 2011, Delft, The Netherlands;
- 3rd International FIG Workshop on 3D Cadastres, 25-26 October 2012, Shenzhen, China;
- 4th International FIG 3D Cadastre Workshop, 9-11 November 2014, Dubai, United Arab Emirates;
- 5th International FIG Workshop on 3D Cadastres, 18-20 October 2016, Athens, Greece.

Closely related to these workshop are the special issues of international scientific journals. Three times the initiative was taken to invite selected authors, based on review of full workshop papers and presentations / discussions at the workshop, to submit a significantly extended / changed version to the special issue. After submitting, the paper has gone through the peer review process of the journal. This resulted in the following three special issues as indicated by their introductions/editorials:

- Christiaan Lemmen and Peter van Oosterom (2002). 3D Cadastres, In: Computers, Environment and Urban Systems, 27, 337–343.
- Peter van Oosterom (2013). Research and development in 3D Cadastres, In: Computers, Environment and Urban Systems, 40, 1-6.
- Peter van Oosterom and Efi Dimopoulou (2018). Research and Development Progress in 3D Cadastral Systems. In: ISPRS International Journal of Geo-Information, 7(2), 5.

The first more concrete versions of texts towards the FIG publication '3D Cadastres Best Practices' was in the form of four overview reports, each presented at the "5th International FIG Workshop on 3D Cadastres", organized in Athens, Greece, 18–20 October 2016:

1. Dimitrios Kitsakis, Jesper Paasch, Jenny Paulsson, Gerhard Navratil, Nikola Vucic, Marcin Karabin, Andréa Flávia Tenório Carneiro and Mohamed El-Mekawy: 3D Real Property Legal Concepts and Cadastre: A Comparative Study of Selected Countries to Propose a Way Forward.
2. Efi Dimopoulou, Sudarshan Karki, Roic Miodrag, José-Paulo Duarte de Almeida, Charisse Griffith-Charles, Rod Thompson, Shen Ying and Peter van Oosterom: Initial Registration of 3D Parcels.
3. Karel Janecka and Sudarshan Karki: 3D Data Management.
4. Jacynthe Pouliot, Frédéric Hubert, Chen Wang, Claire Ellul and Abbas Rajabifard: 3D Cadastre Visualization: Recent Progress and Future Directions.

Discussions during and after the 2016 Workshop resulted in the decision to split Chapter 3 into two parts: one on information modelling and one on data management. The author teams were further reinforced and each produced a next version of their chapters, which were reviewed by colleagues from other author teams. These actions were conducted before the FIG Working Week, Helsinki, Finland, 29 May - 2 June 2017 and discussed at the working week by representatives of each of the chapters. The review comments were processed in the second half of 2017 by the authors teams and all chapters were proof read by native English speakers and finally edited to get an uniform style.

2. CONTENT OF THE FIVE CHAPTERS

In this section the titles, authors and summaries of the five chapters are given for a quick content overview: Chapter 1: Legal foundations, Chapter 2: Initial Registration of 3D Parcels, Chapter 3: 3D Cadastral Information Modelling, Chapter 4: 3D Spatial DBMS for 3D Cadastres and Chapter 5: Visualization and New Opportunities.

2.1 Chapter 1: Legal foundations

The author team consisted of the following persons: Dimitrios Kitsakis, Jesper Paasch, Jenny Paulsson, Gerhard Navratil, Nikola Vučić, Marcin Karabin, Mohamed El-Mekawy, Mila Koeva, Karel Janečka, Diego Erba, Ramiro Alberdi, Mohsen Kalantari, Zhixuan Yang, Jacynthe Pouliot, Francis Roy, Monica Montero, Adrian Alvarado, and Sudarshan Karki.

Summary: The concepts of three-dimensional (3D) real property have been the subject of increased interest in land use management and research since the late ‘90s. Literature provides various examples of extensive research towards 3D Cadastres as well as those that are already implementing 3D cadastral systems. However, in most countries the legal aspects of 3D real property and its incorporation into 3D cadastral systems have not been so rigorously examined. This paper compares and discusses 3D property concepts in 15 cadastral jurisdictions, based on the authors’ national experience, covering Europe, North and Latin America, Middle East and Australia. Each of the legal system in these cadastral jurisdiction are based on different origins of Civil Law, including German, Napoleonic and Scandinavian Civil Law, which can prove useful to research in other Civil Law jurisdictions interested in introducing 3D cadastral systems. These jurisdictions are at different stages of introducing and implementing a 3D cadastral system. This contributes to the detection of the 3D real property concepts that apply as well as deficiencies that prohibit introduction of 3D cadastral systems, while highlighting challenges that may have not yet surfaced in individual jurisdictions. This paper aims to present the different legal concepts regarding 3D real property in the examined countries, focusing on the characteristic features of cadastral objects described as 3D within each country’s legal and cadastral framework. The analysis of the case studies revealed that the countries are on different stages of 3D Cadastral implementation, starting from countries with operational 3D cadastral systems, to others where there is yet no interest in introducing a 3D cadastral system. This paper presents the nature of 3D cadastral objects in each country, as well as differences in the regulatory framework regarding definition, description and registration. The paper continues the legal workshop discussions of the 4th International Workshop on 3D Cadastres in Dubai 2014 by analysing the legal concepts of 3D cadastres in the above-mentioned countries. The outcome is an overview and discussion of existing concepts of 3D property describing their similarities and differences in use, focusing on the legal framework of 3D cadastres. The article concludes by presenting a possible way forward and identifies what further research is needed which can be used to draft national and international research proposals and form legislative amendments towards introduction of national 3D cadastral systems.

2.2 Chapter 2: Initial Registration of 3D Parcels

The author team consisted of the following persons: Efi Dimopoulou, Sudarshan Karki, Miodrag Roić, José-Paulo Duarte de Almeida, Charisse Griffith-Charles, Rod Thompson, Shen Ying, Jesper Paasch, and Peter van Oosterom.

Summary: Registering the rights of a 3D parcel should provide certainty of ownership, protection of rights and unambiguous spatial location. While not all cadastral jurisdictions in the world maintain a digital cadastral database, the concepts of such registration hold true regardless of whether it is a paper-based cadastre or a digital one. Similarly, the motivations and purpose for the creation of a 2D cadastre for individual jurisdictions applies to 3D cadastre as well. It provides security of ownership for 3D parcels, protects the rights of the owners, and provides valuable financial instruments such as mortgage, collateral, valuation and taxation. The current life cycle of the development of a land parcel includes processes start from outside the cadastral registration sphere, such as zoning plans and permits, but has a direct impact on how a certain development application is processed. Thus, in considering the changes required to allow a jurisdiction to register 3D, it is important to note the sphere of influence that could have an impact on 3D registration. These include planners, notaries, surveyors, data managers and registrars; however for the purpose of this paper, the research is

focused on the core 3D aspects that are institutional, legal and technical. This paper explores approaches and solutions towards the implementation of initial 3D cadastral registration, as derived by current procedures of registration of 3D parcels in various countries worldwide. To this end, the paper analyses the categorisations and approaches of 3D spatial units and examines the validation requirements (constraints) on a cadastral database, at various levels of maturity. In this view, 3D data storage and visualization issues are examined in relation to the level of complexity of various jurisdictions, as provided by the results of the country inventory combined with a worldwide survey in 2010 and updated in 2014 (Van Oosterom, et al., 2014). It appears that significant progress has been achieved in providing legal provisions for the registration of 3D cadastres in many countries and several have started to show 3D information on cadastral plans such as isometric views, vertical profiles or text environment to facilitate such data capture and registration. Moreover, as jurisdictions progress towards an implementation of 3D cadastre, much 3D data collected in other areas (BIM, IFC CityGML files, IndoorGML, InfraGML and LandXML) open up the possibility of creating 3D cadastral database and combining with the existing datasets. The usability, compatibility and portability of these datasets is a low cost solution to one of the costliest phases of the implementation of 3D cadastres, which is the initial 3D data capture.

2.3 Chapter 3: 3D Cadastral Information Modelling

The author team consisted of the following persons: Peter van Oosterom, Christiaan Lemmen, Rod Thompson, Karel Janečka, Sisi Zlatanova and Mohsen Kalantari.

Summary: In this chapter we address various aspects of 3D Cadastral Information Modelling. Of course, this is closely related to the legal framework and initial registration as presented in the first two chapters. Cadastral data models, such as the Land Administration Domain Model, which include 3D support, have been developed for legal information modelling and management purposes without providing correspondence to the object's physical counterparts. Building Information Models and virtual 3D topographic/ city models (e.g. LandXML, InfraGML, CityGML, IndoorGML) can be used to describe the physical reality. The main focus of such models is on the physical and functional characteristics of urban structures. However, by definition, those two aspects need to be interrelated; i.e. a tunnel, a building, a mine, etc. always have both a legal status and boundaries as well as a physical description; while it is evident that their integration would maximise their utility and flexibility to support different applications. A model driven architecture approach, including the formalization of constraints is preferred. In the model driven architecture design approach as proposed by the Object Management Group the information model, often expressed in the form of a UML class diagram is the core of the development. This so-called Platform Independent Model (PIM, as presented in the current chapter) is then transformed into Platform Specific Model (PSM). This could be a relational database schema for a spatial DBMS (as will be discussed in the next chapter), or XML schema for a data exchange format or the structure of maps, forms and tables as used in the graphic user interface of a spatial application. Constraints have proved effective in providing the solutions needed to avoid errors and enable maintenance of data quality; thus the need to specify and implement them. This chapter explores possibilities of linking 3D legal right, restriction, responsibilities spaces, modelled with the Land Administration Domain Model (ISO 19152), with physical reality of 3D objects (described via CityGML, IFC, InfraGML, etc).

2.4 Chapter 4: 3D Spatial DBMS for 3D Cadastres

The author team consisted of the following persons: Karel Janečka, Sudarshan Karki, Peter van Oosterom, Sisi Zlatanova, Mohsen Kalantari, and Tarun Ghawana.

Summary: Subdivision of land parcels in the vertical space has made it necessary for cadastral jurisdictions to manage cadastral objects both in 2D as well as 3D. Modern sensor and hardware capabilities for capture and utilisation of large point clouds is one of the major drivers to consider Spatial Database Management Systems (SDBMS) in 3D and organisations are still progressing towards it. 3D data models and their topological relationships are two of the important parts of 3D spatial data management. 3D spatial systems should enable data models that handle a large variety of 3D objects, perform automated data quality checks, search and analysis, rapid data dissemination, 3D rendering and visualisation with close linkages to standards. This chapter asserts that while there has been work done in defining 2D and 3D vector geometry in standards, it is still not sufficient for 3D cadastre purposes as 3D cadastral objects have a much more rigorous definition. The Land Administration Domain Model (LADM), which is an ISO Standard, addresses many of the issues in 3D representation and storage of 3D data in a database management system (DBMS). The chapter further discusses the various approaches to storing 3D data such as through voxels, or point cloud data type and elaborates on the characteristics of a 3D DBMS capable of storing 3D data. Approaches for spatial indexing to improve the fast access of data and the various available options for a 3D geographical database system are presented. Several spatial operations on and amongst 3D objects are illustrated with linkages to the current standards including the LADM. Next, construction of 3D topological and geometrical models based on standards and including their characteristics is discussed. Current 3D spatial database managements systems and their characteristics, including some comparison between selected DBMS including the hardware capabilities are elaborated in detail. Finally, the chapter proposes a 3D topology model based on Tetrahedron Network (TEN) synchronised with LADM specifications for 3D cadastral registration. This topological model utilises surveying boundaries to generate 3D cadastral objects with consistent topology and rapid query and management capabilities. The definition for validation of 3D solids also considers the automatic repair of invalid solids. Point cloud and TEN related data structures available in SDBMSs are also investigated to enable storage of non-spatial attributes so that database updates would store all spatial and attribute information directly inside the spatial database.

2.5 Chapter 5: Visualization and New Opportunities

The author team consisted of the following persons: Jacynthe Pouliot, Claire Ellul, Frédéric Hubert, Chen Wang, Abbas Rajabifard, Mohsen Kalantari, Davood Shojaei, Behnam Atazadeh, Peter van Oosterom, Marian de Vries, and Shen Ying.

Summary: This chapter proposes a discussion on opportunities offered by 3D visualization to improve the understanding and the analysis of cadastre data. It first introduce the rationale of having 3D visualization functionalities in the context of cadastre applications. Second the publication outline some basic concepts in 3D visualization. This section specially addresses the visualization pipeline as a driven classification schema to understand the steps leading to 3D visualization. In this section is also presented a brief review of current 3D standards and technologies. Next is proposed a summary of progress made in the last years in 3D cadastral visualization. For instance, user's requirement, data and semiotics, and platforms are highlighted as main actions performed in the development of 3D cadastre visualization. This review could be perceived as an attempt to structure and emphasise the best practices in the domain of 3D cadastre visualization and as an inventory of issues that still need to be tackled. Finally, by providing a review on advances and trends in 3D visualization, the paper initiates a discussion and a critical analysis on the benefit of applying these new developments to cadastre domain. This final section discusses about enhancing 3D techniques as dynamic transparency and cutaway, 3D generalization, 3D visibility model, 3D annotation, 3D data and web platform, augmented reality, immersive virtual environment, 3D gaming, interaction techniques and time.

3. THE FUTURE OF 3D CADASTRES, THE NEXT STEPS

The FIG publication '3D Cadastres Best Practices' hopes to provide a clear and comprehensive overview to both the newcomers and experts in the 3D Cadastres community. For sure this is just a snapshot of the current state and our knowledge must further evolve with the many challenges that are ahead of us, including the emerging mega-cities due to further urbanization. Many developments are ahead of us and to name just a few: revision of LADM (with potentially more detailed 3D spatial profiles), Marine Cadastre, deep integration of 3D space and time (4D Cadastre), new data acquisition techniques (including VGI), growing information infrastructure (of which Land Administration is a part), and new visualization and dissemination techniques (including VR and AR). Already, the next step of our on-going journey is planned: the 6th International FIG Workshop on 3D Cadastres, to be organized in Delft, The Netherlands, 2–4 October 2018. And also this time a special issue on 3D Cadastres is planned: to be published in Land Use Policy (2019 or 2020).

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It was a great pleasure to be involved in the creation of the FIG publication '3D Cadastres Best Practices'. This was mainly due to the constructive and open collaborations of all involved. First of all I would like to thank the lead authors, the authors of chapters in the publication, but also the authors of papers at past FIG 3D Cadastres workshops and other FIG events, for their continuous contributions to the field of 3D Cadastres. Next, it is important to remember the hard work the reviewers (programme committees members) have put into all their constructive comments and adding many ideas and views to those of the original authors. Many, many thanks for this often rather invisible task. Finally, I would like to thank Sudarshan Karki for the English proof reading of an incredible amount of pages and Dirk Dubbeling for the last checks and formatting to make sure the publication gets an uniform look and feel. Great teamwork, thanks for the many years of collaborations.

Prof Peter van Oosterom,
chair of the FIG 3D working group on 3D Cadastres

Chapter 1. Legal foundations

Dimitrios KITSAKIS, Greece, Jesper M. PAASCH, Sweden, Jenny PAULSSON, Sweden, Gerhard NAVRATIL, Austria, Nikola VUČIĆ, Croatia, Marcin KARABIN, Poland, Mohamed EL-MEKAWY, Sweden, Mila KOEVA, The Netherlands, Karel JANEČKA, Czech Republic, Diego ERBA, Argentina, Ramiro ALBERDI, Argentina, Mohsen KALANTARI, Australia, Zhixuan YANG, China, Jacynthe POULIOT, Canada, Francis ROY, Canada, Mónica MONTERO, Costa Rica, Adrián ALVARADO, Costa Rica, and Sudarshan KARKI, Australia

Key words: 3D cadastre, 3D real property, legal framework, land management, land administration

SUMMARY

The concepts of three-dimensional (3D) real property have been the subject of increased interest in land use management and research since the late '90s. Literature provides various examples of extensive research towards 3D Cadastres as well as those that are already implementing 3D cadastral systems. However, in most countries the legal aspects of 3D real property and its incorporation into 3D cadastral systems have not been so rigorously examined. This paper compares and discusses 3D property concepts in 15 cadastral jurisdictions, based on the authors' national experience, covering Europe, North and Latin America, Middle East and Australia. Each of the legal system in these cadastral jurisdiction are based on different origins of Civil Law, including German, Napoleonic and Scandinavian Civil Law, which can prove useful to research in other Civil Law jurisdictions interested in introducing 3D cadastral systems. These jurisdictions are at different stages of introducing and implementing a 3D cadastral system. This contributes to the detection of the 3D real property concepts that apply as well as deficiencies that prohibit introduction of 3D cadastral systems, while highlighting challenges that may have not yet surfaced in individual jurisdictions. This paper aims to present the different legal concepts regarding 3D real property in the examined countries, focusing on the characteristic features of cadastral objects described as 3D within each country's legal and cadastral framework. The analysis of the case studies revealed that the countries are on different stages of 3D Cadastral implementation, starting from countries with operational 3D cadastral systems, to others where there is yet no interest in introducing a 3D cadastral system. This paper presents the nature of 3D cadastral objects in each country, as well as differences in the regulatory framework regarding definition, description and registration. The paper continues the legal workshop discussions of the 4th International Workshop on 3D Cadastres in Dubai 2014 by analysing the legal concepts of 3D cadastres in the above-mentioned countries. The outcome is an overview and discussion of existing concepts of 3D property describing their similarities and differences in use, focusing on the legal framework of 3D cadastres. The article concludes by presenting a possible way forward and identifies what further research is needed which can be used to draft national and international research proposals and form legislative amendments towards introduction of national 3D cadastral systems.

1. INTRODUCTION

Cadastres are being recognized as the core of land administration systems. The cadastral map or plan should be able to represent complete and comprehensive spatial information for registering land rights, restrictions and responsibilities (RRRs) on the land parcels (Kaufmann and Steudler, 1998). However, until today most of the countries around the world use 2D land parcels as the base for their land administration systems (Ho et al., 2015), regardless of the 3D characteristics implied by the relative real property legislation. Thus, presentation of RRRs through 2D projection of land parcels cannot accommodate complex, overlapping real property so it needs to be extended to three-dimensional (3D) space and properties. Contrast between 3D real property implications in legislation and its 2D registration and documentation is becoming more emphasized with the increasing development of urban areas with complex structures, high-rise buildings and underground infrastructures. The rights of cadastral objects may relate to spaces above or below the Earth's surface (Stoter et al., 2011). More complex relationships in vertical space can no longer be unambiguously mapped onto the Earth's surface in 2D. Pressure on land use, especially in the city centres, has led to dense construction with complex structures with intertwined relationships. In general, registration of rights is possible on parts of the building, however, the spatial representation of the extension of rights often does not exist or it is possibly stratified on two-dimensional representation. In addition, an increasing number of tunnels, underground networks and infrastructure objects (e.g. water, gas, electricity, telephone, Internet and other pipe networks) under or above land are not owned by the owner of the land above or below (Roić, 2012).

The concept of three-dimensional (3D) real property has been the subject of increased interests in land use management and research during the last decade while it has been in focus for more than one and a half decade along with the discussion about how to secure rights in space (Fendel, 2002; Stoter and v. Oosterom, 2006; Ploeger, 2011; Stoter et. al., 2012; v. Oosterom, 2013; Paasch and Paulsson, 2014; Kitsakis et al., 2016). General questions such as registration of properties in strata (i.e. in layers) have been discussed. What "3D property" is depends, to a large extent, on the legal system and cultural background (Fendel, 2002). Since then, the problems of finding definitions have been addressed by e.g. Paulsson (2007) and Sherry (2009). Paulsson (2007) concludes that there does not seem to be a simple meaning to the concept of 3D property. Research has been carried out concerning the legal framework of 3D cadastres aiming at identifying the main topics concerning the legal aspects of 3D property and cadastre (see, e.g. Paasch et al., 2016).

There are several countries already implementing 3D cadastres, such as Sweden, Norway, Australian states of Victoria and Queensland, in Canada Brunswick and British Columbia, as well as Chinese cities such as Shenzhen. However, in most cases the legal aspects of 3D real property and its incorporation into 3D cadastral systems have not been so rigorously examined (see e.g. Paulsson and Paasch, 2013).

This chapter provides a comparison and discussion of 3D property concepts in selected countries, which are chosen based on the professional experience of the authors. Currently they are in different stages in their 3D cadastral development. In addition to that, the authors aim through this chapter to provide input to countries that are exploring or are in the midst of the process of developing a 3D cadastral system, especially from a legal perspective. Since the countries are on different stages of introducing and implementing the 3D cadastral systems this study contributes to the detection of main 3D real property concepts that apply internationally as well as deficiencies and malfunctions that prohibit introduction of 3D cadastral systems. To compare between these countries, a set of criteria was proposed to provide a systematic comparative analysis.

The remainder of this chapter is structured as follows. Section 2 presents the topics examined in each of the fifteen case studies. In Section 3, previously examined topics are summarised in tables, while their similarities and differences are presented and analysed. Section 4 presents the conclusions derived through preceding comparative analysis. The chapter ends by presenting issues emerging from current study that require further research.

2. 3D LEGAL ISSUES EXEMPLIFIED BY CASE STUDIES

There are several countries already implementing 3D cadastres and literature provides numerous publications on 3D cadastres' developments (e.g. Karki et al., 2011; Mangioni et al., 2012; Stoter et al., 2012). The examples in this chapter highlight different, national concepts of 3D property, covering Europe (Austria, Bulgaria, Croatia, Czech Republic, Greece, The Netherlands, Poland and Sweden), South America (Argentina and Costa Rica), Asia (China and Jordan), Australia (State of Queensland and Victoria) and Canada (Province of Quebec).

Investigation of 3D real property aspects in each of the examined countries starts by providing information on general characteristics of national real property legislation in the form of the following questions:

- What was the reasons to introduce a 3D system or why would it be necessary?
- What is the current status?
- What is the legal definition of 3D objects and what are the possibilities for delimitations?
- What types of rights can be registered in 3D?

To facilitate this procedure the following aspects were examined:

- How is real property defined in law (Land Code, Civil Code, or any other legal document in each country that defines land)? Is the third dimension implied/clearly defined in the legal definition?
- What are the 3D object situations (including every situation regardless it's recording in cadastre, or if it is defined by law)? - What are the 3D objects recorded in national registries and how are they recorded (e.g. 2D plans + floor number, 3D pdfs, 2D projections etc.)? Which registries are used to record these objects?
- Are there any restrictions or responsibilities implying 3D aspects (or directly defined in 3D) defined by law?
- How is 3D space separated from land ownership in case of underground/above ground infrastructures (e.g. real property stratification, specific legislation, servitude establishment etc.)? This requirement mostly refers to Civil Law jurisdictions, where Roman principles significantly restrict partition of 3D space.

In the following section, above mentioned aspects are presented for each jurisdiction, in alphabetical order.

2.1 Argentina

2.1.1 Background information

In Argentina, property rights are fundamental rights ensured by the National Constitution. Until 2015, the Civil Code of the Nation, approved in September 25, 1869, condensed the bases of the legal order in civil matters. During this period, the property had a vertical development, and even when the owner could exercise his/her property right in different ways, there were some restrictions. The volumetric definition of the property found in that Civil Code was not evident in the National Law of Cadastre (Ley Nacional de Catastro No. 26.209/2007), which shows an inconsistency in the national regulatory framework. On August 1, 2015, a new legal framework was developed: the Civil and Commercial Code of the Nation came into force and it brought up several changes related to 3D Cadastral concepts, but its application is in transition within the provinces' legal framework.

Property rights are registered in titles or deeds, physically written and stored in the Property Registry. These documents include the name of the beneficiaries and a brief, and usually unreliable, estates description. In parallel, the parcels are registered in cadastral institutions by a paper cartographic document named "blueprint of surveying", that provides some kind of graphic and alphanumeric information about the parcel boundaries. In most cases, cadastres do not share databases with the Property Registry; they can only exchange specific information. Some provincial cadastres have digital databases based on blueprints plus legal and economic information (basically holders, restrictions and tax valuation). Most of them have established a Geographic Information System to manage databases, but still many institutions work with paper documents (in all registry stages), even 3D legal objects.

Even when the Civil and Commercial Code of the Nation imposes all real rights and some restrictions, each province organize its Cadastre and Property Registry under its proper law. Not all of the provincial law adhered to the National Law of Cadastre.

In this context, the legal framework doesn't provide 3D conceptual and legal framework to improve cadastral institutions, neither does it promote transition from physical to digital databases.

2.1.2 Status of 3D objects' recording

The complex reality of cities in terms of RRR materialized when different kinds of 3D objects started to highlight the necessity of a 3D information system. Beside this, the new concepts of rights written in the 2015 Civil and Commercial Code demonstrate that 2D parcels cannot accommodate the complex overlapping of real property. Despite this reality, Argentina is not exploring a 3D cadastral system yet, particularly from the legal perspective. There are some discussions in academic events, but even in jurisdictions where the cadastral norms are changing, the 2D paradigm is still present.

The absolute 3D representation of buildings is not a common practice in Argentine cadastres. The 3D representation prototypes are generally generated in a GIS environment, showing the building as a function of the number of floors (the alphanumeric database indicates this value, which is multiplied by 3 meters to generate the volume). Most of the 3D objects are represented in 2D plans plus a number that normally corresponds to the floor, and a cross-section with identification of heights relative to the ground in case of buildings (Figure 1), and a topographic profile, in the case of towpath (Figure 2).

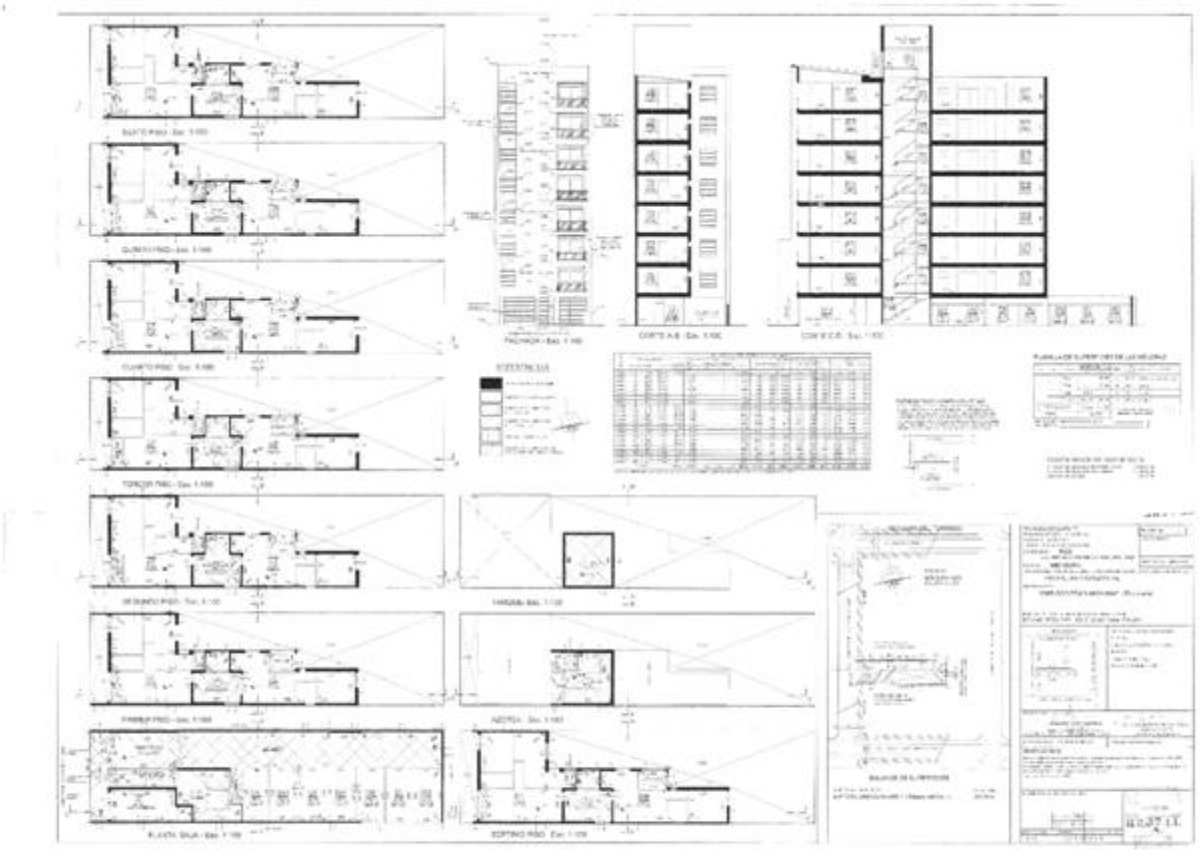


Figure 1: Survey blueprints of horizontal property

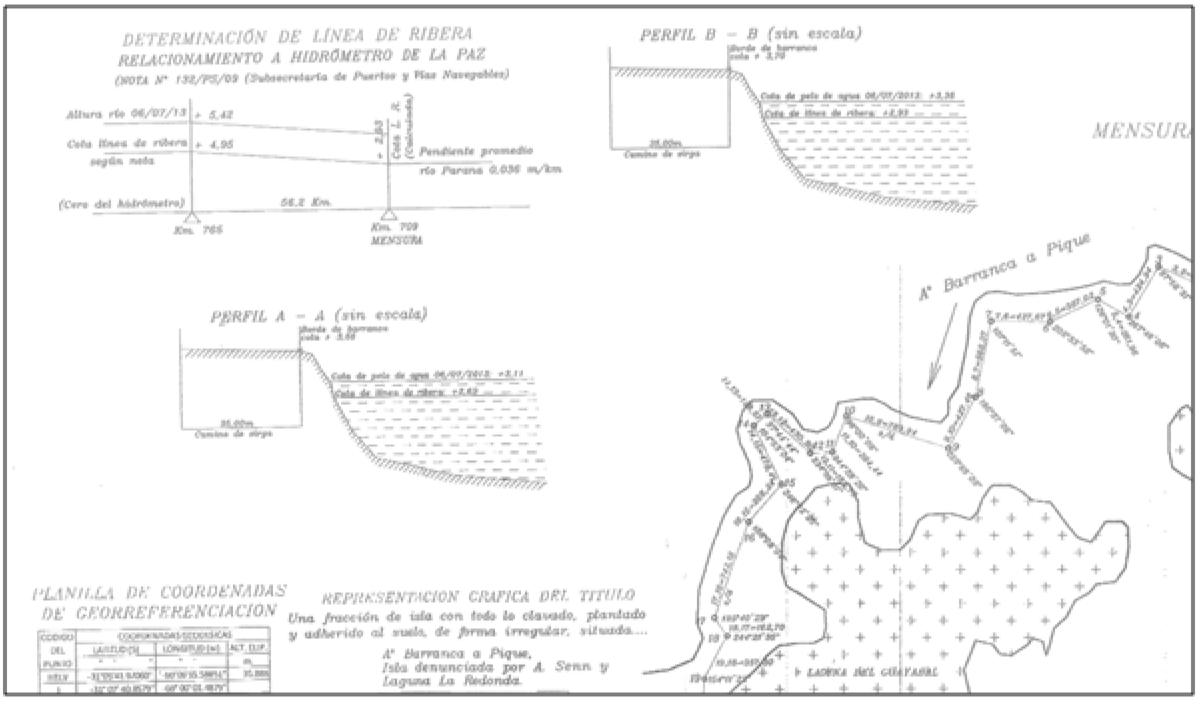


Figure 2: Survey blueprints of riparian and towpath

2.1.3 Legal definition of 3D objects

According to the Civil and Commercial Code of the Nation, there are two kinds of private properties: Properties by Nature, which is the land and other things incorporated to it by man or under the ground but without human intervention (Art. 225), and Properties by Accession, which are things immobilized by adhesion to the ground. In both cases, it could be said that the 3rd dimension is implicit.

The concept of 3D parcel does not exist officially in Argentina. All the parcels are defined in 2D according to the Cadastral National Law No. 26209, which says: "… a parcel is a representation of a continuous real estate territory identified by a polygonal boundary with one or more legal titles of possession, whose existence and essential elements are recorded in a cartographic document registered in the cadastral institution" (Art. 4).

The Cadastral National Law defines a "territorial object" as any portion of the territory that, by nature, is finite and homogeneous. The law defines the "legal territorial object" too as those generated by a legal cause which may be a property title (as is the case in real estate transactions), an ordinance or law (as is the case in ownership restrictions, the creation of reservation areas, or the demarcation of an urban area), or even an international treaty (such as those that establish the borders between countries). The law stipulates that all the legal objects and their public records must be managed by the provincial cadastres. Furthermore, the record of titles is responsibility of the Register of Property. The institution is separated from the provincial cadastre; however, the databases are shared. In fact, the information about ownership stored in cadastral databases came from the Registers. At the same time, in the property titles, notaries write a brief description of the parcel's boundaries, and usually it refers to the respective blueprints. Both institutions are tightly related and they need each other to complete the record of RRR.

2.1.4 Types of rights that can be registered in 3D

Horizontal Property: right that can be exercised over a property of its own. It gives to the owner the powers of use, and material and legal disposition. It can be exercised over private parts and over common parts of a building, in accordance with what established the respective regulations of horizontal property constitution (Art. 2037 of the Civil and Commercial Code). The registration of rights into the volume of a building is perfectly possible and clear in the cadastral map of horizontal properties. The spatial representation of the extension of rights above the roof and below the lowest garage does not exist.

Surface Right: Temporary real right that is constituted on a foreign property. It grants to the owner, the faculty of use, enjoyment and material and legal right to plant, forge or build, or planted, forested or constructed in the land, the air space or underground, according to the modalities of its exercise and term of duration established in the title sufficient for its constitution and within the provisions of this Title and the special laws. The surface right does not mean a land modification, but an affectation. It can be established on the top of the building.

Rivers and lakes boundaries: the riparian line is a boundary that divides the public and private property rights, separating river (public domain) of land (private domain). It must be determined from the average ordinary maximum floods level (Art. 1960), it is a vertical surface which involves water levels. Associated with it, there is the towpath: a restriction to private ownership established in Art. 1974 of the Civil and Commercial Code, defined as a 15 m strip measured from the riparian line of water bodies, toward the interior of adjoining properties.

Active Real Estate Easements: under Title XI – Easements, Chapter 1 – General Dispositions, the Civil and Commercial Code define an easement (servidumbre) as a real estate right, permanent or temporary, exercised over a property owned by others. It is a restriction to the right of ownership by the property titleholder. An easement requires two real estate properties, a master and a slave, which must belong to different owners. It can be established at any elevation level (floors, terraces, etc.)

Administrative Easements of Utility Pipes (electrical conduits, gas pipes, etc.): the National Law No. 19.552/1972 for electrical conduits and the National Law No. 17.319/1967 for hydrocarbons, stipulate that administrative easements for ducts, affect ownership by imposing restrictions and limitations needed to build, maintain, repair and use a pipe or duct that is an essential component of an energy system. These administrative easements are represented graphically as areas or surfaces, with no consideration for the height (electrical conduit) or depth (gas pipe) at which they are laid.

Rights Granted under the Mining Code: Established by Decree No. 456/1997, it regulates the property of mines, and the rights of exploration and operation. Art. 7 stipulates that the mines are private assets of the Federal Government or the Provinces, depending on their location. Art. 10 stipulates that, “independently of the original ownership by the State… the private property of the mines can be established by legal grant”. This granting of mining rights can be interpreted as a mining easement to the mining company. On the other hand, Art. 12 defines mines as real estate properties. Art. 20 establishes a mining cadastre to describe the physical, legal, and other useful information about mining rights. Those rights are identified with points that represent the vertices of the “area” defined in the requests for exploration permits, discovery manifests, etc. However, the Mining Code does not mandate in any of its articles the volumetric representation of the mineral to be explored.

Restrictions under the Aeronautic Code: established by National Law No. 17.285/1967, the Aeronautic Code describes the limitations to ownership of property located close to airports. It defines the limits to obstacles in the airspace in airports and their surrounding environment, to ensure the secure landing and take-off of aircrafts. Although these obstacles are by nature volumetric bodies, they are represented by their projections on the representation surface. Cross-sections are also enclosed to describe the height over land over which the restriction extends.

2.1.5 Concluding remarks

The idea of a 3D system that extends to three-dimensional space is still embryonic in Argentina. There are a few academic researches only. The introduction of a 3D system is not going to happen soon in the country particularly because, even not having an official explicit definition at the national legal framework, the terms "3D property" and "3D parcel" are not part of the legal terminology in the country.

The georeferencing of cadastral parcels and the territorial objects under the same system (even in 2D) is still incipient for the urban areas. It could represent the first step to establish a 3D cadastre in Argentina. Even though the provincial cadastres are still independent, their points of contact with the municipal cadastres could accelerate the process of creating territorial data in 3D. The public and private utilities and the organizations that control the environment and air traffic must structure their data under the same system of reference as the territorial cadastres, representing their structures with equivalent precision.

2.2 Australia (State of Queensland)

2.2.1 Background Information

Queensland is in the north-east seaboard of Australia and is the second largest state in Australia with an area of 1.8 million square kilometres. There are more than 3 million total parcels of which around 300,000 are building units and around 4500 are volumetric parcels in the Digital Cadastral Database (DCDB). The Department of Natural Resources and Mines is the custodian of all cadastral data.

Queensland is one of the pioneering and leading jurisdictions in 3D cadastre and 3D registration. The Building Units and Group Titles Act (1980) has been registering building units and common properties in the cadastral system for the last 37 years and 3D volumetric parcels for the last 20 years since 1997. Currently there are two very important projects underway in Queensland; one is a cadastral and geodetic systems review project with an aim to consolidate all cadastral and geodetic databases as well as to include 4D in the database, and the second is 3D QLD initiative which aims to provide 3D indoor navigation and 3D augmented reality through cadastral database (http://3dqld.org/).

2.2.2 Status of 3D object's recording

In Queensland all titles are registered and maintained by the Titles Registry Office (Karki, 2013). For the purposes of registration of titles, all 2D and 3D titles are treated the same and registered similarly (Karki, Thompson, & McDougall, 2013). The Land Title Act (1994) and the Land Act (1994) are the main acts for registration of freehold and non-freehold lands respectively. Building units are registered under Building Units and Group Titles Act (1980) and Body Corporate and Community Management Act (1997). Almost all freehold land is surveyed by private licensed cadastral surveyors. The Surveying and Mapping Infrastructure Act (2003) guides surveyors and assists in maintaining survey infrastructure, the Surveyors Act (2009) guides the activities of surveyors and provide protection for the landowners. The Sustainable Planning Act (2009) administered by the local governments guides surveyors by managing development zones. In addition there are several directives for surveyors and land practitioners; the Land Practice Manual, the Cadastral Survey Requirements (CSR) and the Registrar of Titles Directions for Preparation of Plan (RTDPP). All these legislation and directives have provided a robust legal framework for the registration of 3D titles which is assured by the state through the Torrens titles registration system.

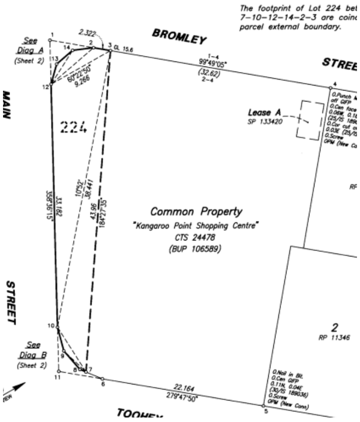
2.2.3 Legal definition of 3D objects

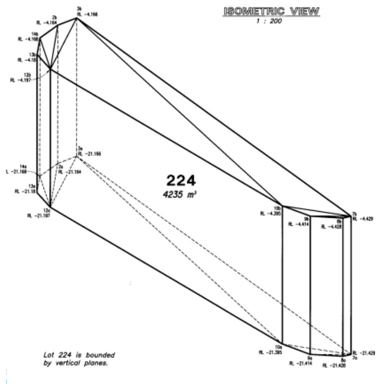
Section 10.2 and 10.5.1 of the RTDPP allows any kind of 3D object to be registered as long as they can be defined mathematically. There is a separation between the 2D plans (called Standard Format Plan), 3D building unit plans (called Building Format Plan (BFP)) and 3D volumetric

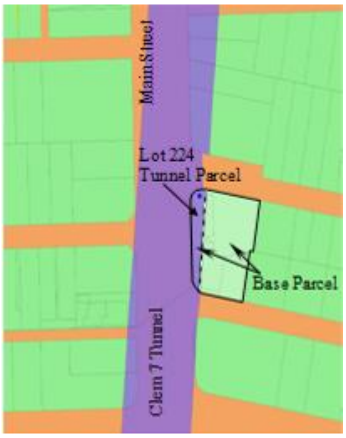
plans (called Volumetric Format Plans (VFP)). While separate legislation exists for building units, volumes are dealt under the directives of the RTDPP.
The 3D cadastral plans (BFP and VFP) show 2D footprints on 2D base lot with 3D Isometric views that are part of the cadastral plan. 3D objects have different lot numbering systems to distinguish themselves from a 2D lot number. 3D Volumetric plans show connection to geodetic control point for height datum and dimension and bearings of objects. Distinction is made between the terminology lot and parcel. Lot is the surface or the base parcel whereas parcel is contained within a lot and is the various units/apartments, common property, volumes etc. within the bounds of a surface parcel. Where the lot does not have any other parcel, such as in the case of a 2D lot, the lot and parcel are often used interchangeably and is understood from the context.
The land registration process has evolved through Common Law. Torrens titles system is used for titles registration and paper titles are not provided to owners but rather stored in a Titles database. This information can be purchased for a small fee and is frequently accessed by banks, real estate agents, solicitors and conveyancers etc. but is protected by privacy acts. The point of truth for title is the Titles Registry Office record, and for parcel dimensions is the paper cadastral plan. Private cadastral surveyors survey the land and are legally responsible for the accuracy of plan data while the State is responsible for the title. There are differences in the representation of the paper cadastral plan in the Digital Cadastral Database (DCDB). The cadastral plans have a great deal of detail regarding the survey such as dimensions, reference marks, geodetic control points, encroachment information, details of past surveys, isometric views, leases, covenants etc. The DCDB does not display these additional information and simply shows the parcel polygon and other attributes such as tenure type, ownership details including all other RRR. Thus the paper plan is the point of truth for cadastral data, not the DCDB which is just a graphical representation of the information from the cadastral plan and the Titles office. The digital cadastral database is a representation only and not the point of truth. Both the Titles Office and Directorate of Survey is within the Department of Natural Resources and Mines, but are separate entities. All cadastral representation, including valuation, topographic data, imagery etc. are open source and is disseminated free of charge.

2.2.4 Types of rights that can be registered in 3D

All RRR on 3D are registered and any RRR that is possible to be registered on 2D is also possible to be registered on 3D parcels. Figure 3 shows some examples of 3D parcels registered in Queensland. The 3D parcel is truncated and separate 3D lots are created for each volume at the intersection of the extent of the 2D lot at the surface or with the intersection with another volumetric parcel. The 3D objects registered in Queensland are 3D Easements, Leases, Covenants; 3D Roads; Air spaces; 3D Ambulatory boundaries; Water Spaces; Underground space (with or without construction); Restriction easements (e.g. so others cannot obstruct view); Mining rights; Limitations (above or below a certain height); Apartments and Common Property; Tunnels, Utilities (network and individual infrastructure); Carbon abatement zones; Commercial spaces; Car parks (including the incline plane); Bridges (pylons and bridge spaces); Sports spaces (stadium, locker spaces) etc.

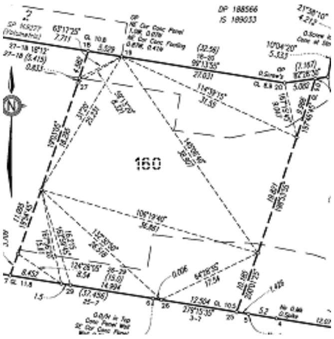


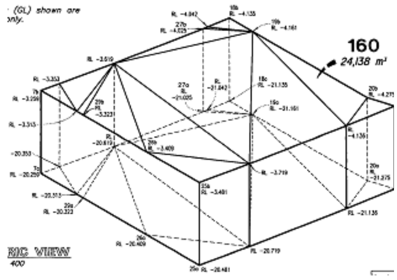




(a) 3D Footprint on cadastral plan (b) Isometric view on cadastral plan (c) DCDB representation

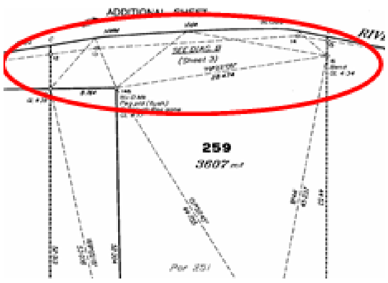
Example of 3D parcel (Clem 7 Tunnel) being constrained to surface 2D parcel

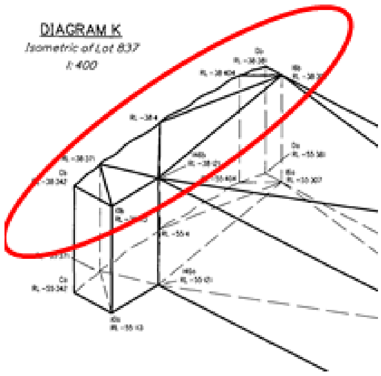


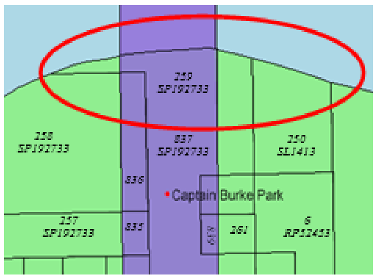


(a) 3D Footprint on cadastral plan (b) Isometric view on cadastral plan (c) DCDB representation

Example of intersecting 3D parcels (Clem 7 Tunnel and Busway)

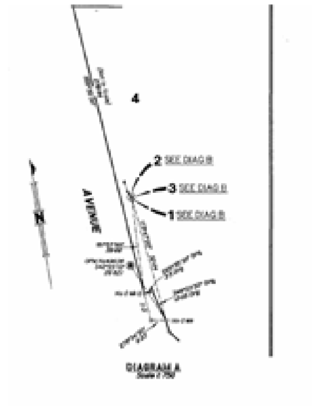


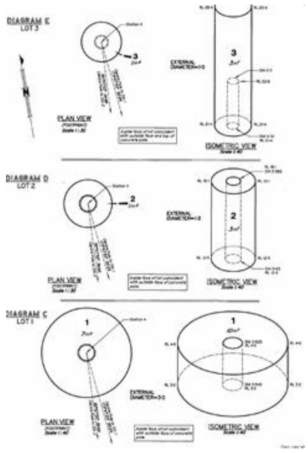


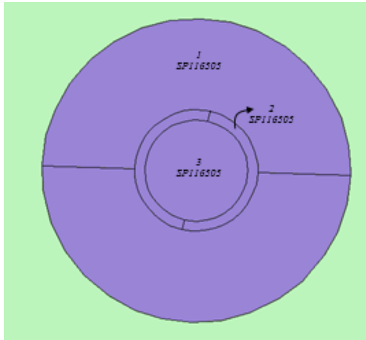


(a) 3D Footprint on cadastral plan (b) Isometric view on cadastral plan (c) DCDB representation

Example of 3D ambulatory boundary (Clem 7 Tunnel and Brisbane River)

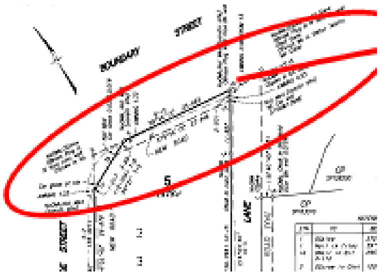


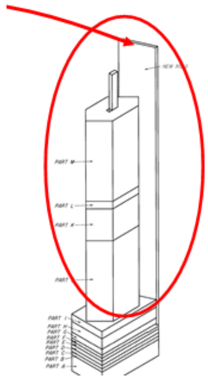




(a) 3D Footprint on cadastral plan (b) Isometric view on cadastral plan (c) DCDB representation

Example of registered 3D airspace for utility network infrastructure





(a) 3D Footprint on cadastral plan (b) Isometric view on cadastral plan (c) DCDB representation

Example of reserved airspace for 3D road parcel

Figure 3: Examples of 3D volumetric parcels registered in Queensland (Karki, 2013)

2.2.5 Concluding remarks

Queensland has a long history of legislative support for registering 3D cadastral objects. Since the registration of 3D is treated similar to 2D and the Title is supported by the state, the owners, developers, surveyors, mortgagers etc. have no issue in creating, maintaining, registering, transferring, and mortgaging 3D parcels. Also, since the digital cadastral database is not considered the point of truth, the lack of recording of 3D in a database is not seen as a hindrance in the development of 3D parcels. Queensland is further investing in the development of a 3D capable database as well as enhanced functionalities such as 3D indoor navigation and 3D augmented reality using data from a 3D cadastre.

2.3 Australia (State of Victoria)

2.3.1 Background information

The State of Victoria is located in the south-eastern corner of Australia. It is the geographically smallest mainland state, but the most densely populated and urbanised. Victoria is the second most populous Australian state with an estimated population of 6,100,900 as at June 2016 and a total land area of 227,420 Km2 (ABS 2016). The Victorian land administration system is called Land Use Victoria which is the principal agency for land administration, property data and helping with better use of government-owned land.

2.3.2 Status of 3D objects' recording

Legislation has evolved in Victoria over an extended period to meet the demands for recording rights, restrictions and responsibilities (RRRs) related to the ownership of the 3rd dimension of space. The evolution has been driven by the requirements of developers, owners, lending and financial institutions, mortgagees and planners. The current legislation governing the registration of land RRRs including 3D RRRs is the Subdivision Act 1988 (Aien et al. 2013). The land registration involves issuing a certificate of title that is complemented by a graphical representation of the spatial extent of the RRRs associated with the land known as the subdivision plan. Victoria's current legislation allows for registration of 3D land RRRs; however, the techniques for graphically depicting them in subdivision plans rely on 2D representation such as 2D cross–section and floor plan.

2.3.3 Legal definition of 3D objects

In legally defining 3D RRRs, two fundamental pieces of information is used; one is the type of 3D RRRs and second is the boundaries by which the spatial extent of the RRRs is defined. In practice the RRRs that are registered in Victoria include lot (private interest), common property (communal interest), roads (public interest), reserve (park and green spaces in public interest), crown land (land in interest of government) easement (utility network interest), restriction (limitation on the use of land), depth limitation, and airspace (above the ground/ external building interest). The types of boundaries that are used in legally defining the 3D RRRs include structural, ambulatory and projected. Structural boundaries are defined based on building parts e.g. walls. Projected boundaries are used to define invisible boundaries e.g. balconies. Ambulatory boundaries are based on dynamic natural features e.g. river borders (Atazadeh et al 2017).

2.3.4 Types of rights that can be registered in 3D

In most cases, roads, easements, reserves, crown lands and restrictions are 2D RRRs. But 3D lots, common property, depth limitation and airspace are common 3D RRRs and registered in different ways and methods.

Apartment units are registered as lots. An apartment unit may include accessory parts such as parking space and storage space. Apartments and its accessory parts are registered under one title. Common property is another type of 3D RRRs that is registered as communal legal spaces (such as corridors and lobbies) and physical structures (such as walls and ceilings). 2D cross-section and floor plan views of only apartments and communal legal spaces are represented, and communal physical structures are only described in the subdivision plans. Depth limitation and airspace are registered as 3D RRRs. They describe but are not delineated in subdivision plans (Atazadeh et. al. 2016).

2.3.5 Concluding remarks

Victorian regulations have a longstanding track record in facilitating registration of 3D RRRs. The laws and regulations in Victoria have evolved such that it is one of the lead jurisdiction in 3D cadastres. While the registration of 3D RRRs is for many years, 3D presentation of them is not functional yet. Land Use Victoria in conjunction with the University of Melbourne leads the way to establish and realise Victorian 3D digital cadastral system (figure. 4) (Shojaei et. al. 2016).

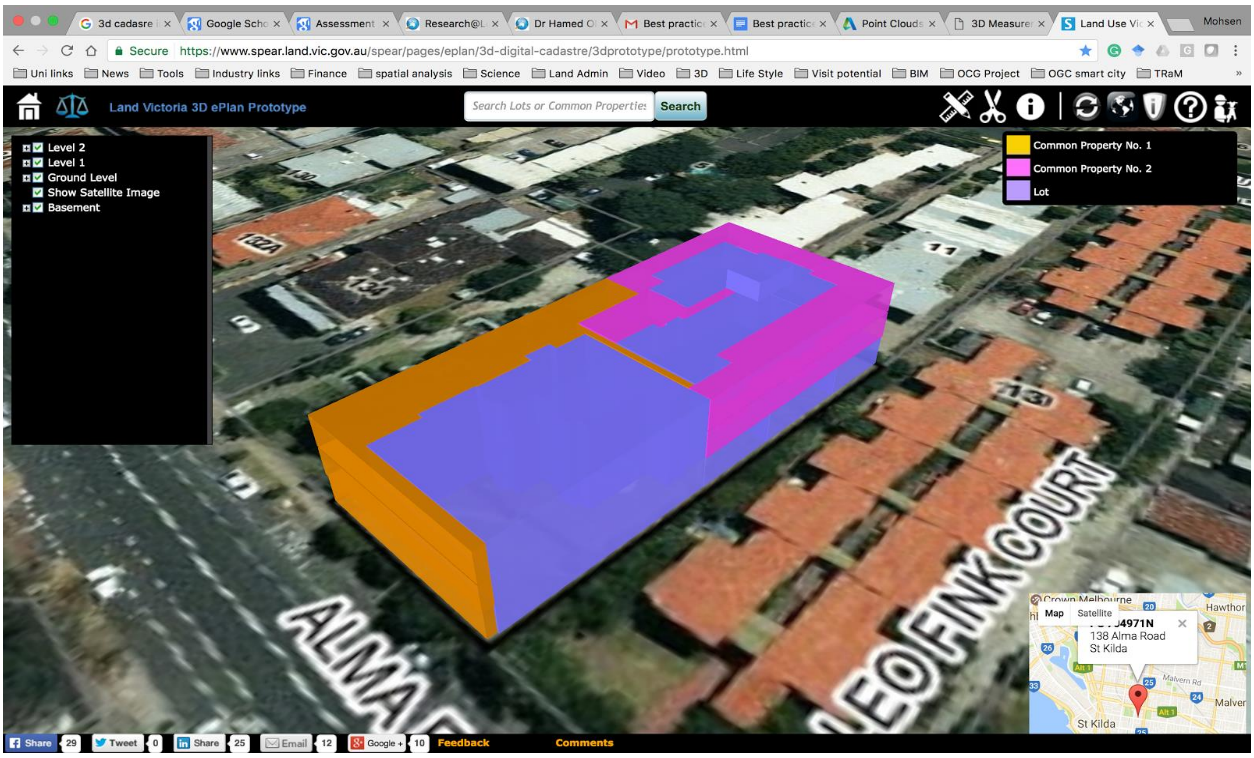


Figure 4: A prototype 3D cadastre system developed by Land Use Victoria accessed https://www.spear.land.vic.gov.au/spear/pages/eplan/3d-digital-cadastre/3dprototype/prototype.html

2.4 Austria

2.4.1 Background information

The Austrian cadastral system has a long tradition. The current system was initiated in 1817 and developed since that time (for details see Lisec and Navratil, 2014). Currently, the focus of the cadastral authority is on digitizing the survey archive, a project that will be finished in 2024 (Lichtenberger et al. 2015). Since this effort requires significant resources, other endeavours, like the realization of a 3D cadastre, have to be postponed. The ownership of land is defined in the Civil Law code. Theoretically the vertical extent is not restricted, i.e., ownership ranges from the centre of the earth to infinity. In practice, however, the ownership right ends where other public rights restrict private ownership, e.g., international airspace or mining rights. The system adopts title registration and thus data on ownership and other rights can be trusted.

2.4.2 Status of 3D objects' recording

In 2007 the question, whether Austria needs a 3D cadastre or not, was raised (Navratil and Hackl, 2007). The paper discussed the principles of the Austrian cadastral system and shows that it is possible to register rights on parts of a parcel. A right of way, for example, can be restricted to a specific path. However, the spatial restriction can only be defined in 2D.
Several types of real 3D objects are registered in the Austrian cadastre: tunnels, condominiums, and traditional wine cellars. Tunnels are not shown on the cadastral maps but they can be registered as restrictions on the land register. The wine cellars are connected to a small building

with the winepress and there a tunnel starts where the barrels are situated. The cadastral map shows a small building and a dashed boundary line where the tunnel starts. The actual geometry, the length, and the depth of the tunnel are unknown. The legal construction of condominium is quite elaborate. Figure 5 shows an example of the documentation. Each owner of an apartment is a shared owner of the land (compare Fig. 4c: “Ingeborg” and “Heinz Ing.”) and has an exclusive use right of his apartment (specified in the purchase contract). The share is determined by the size of his apartment in relation to the total area of all apartments on the parcel. A document, the “Parifizierungsplan”, registered in the land registry, describes the geometry of the whole construction and shows all apartments and stipulates the utility value for each apartment (shown in Fig. 4b). The cadastral map, however, does show neither the apartment structure nor the spatial distribution of use rights. Since the “Parifizierungsplan” contains all building floors, it could be used as a starting point for a 3D representation of condominium, however, analysis of this is ongoing.

2.4.3 Concluding remarks

The surveying authority in Austria, the Federal Office of Metrology and Surveying (BEV), is carefully observing the international trends. However, the current budget does not allow implementing multiple large projects simultaneously and the current digitizing process of the survey archive requires significant resources. Thus, Austria, although quite interested in the topic of 3D cadastres, will have to postpone implementation and restrict to research in the next years.

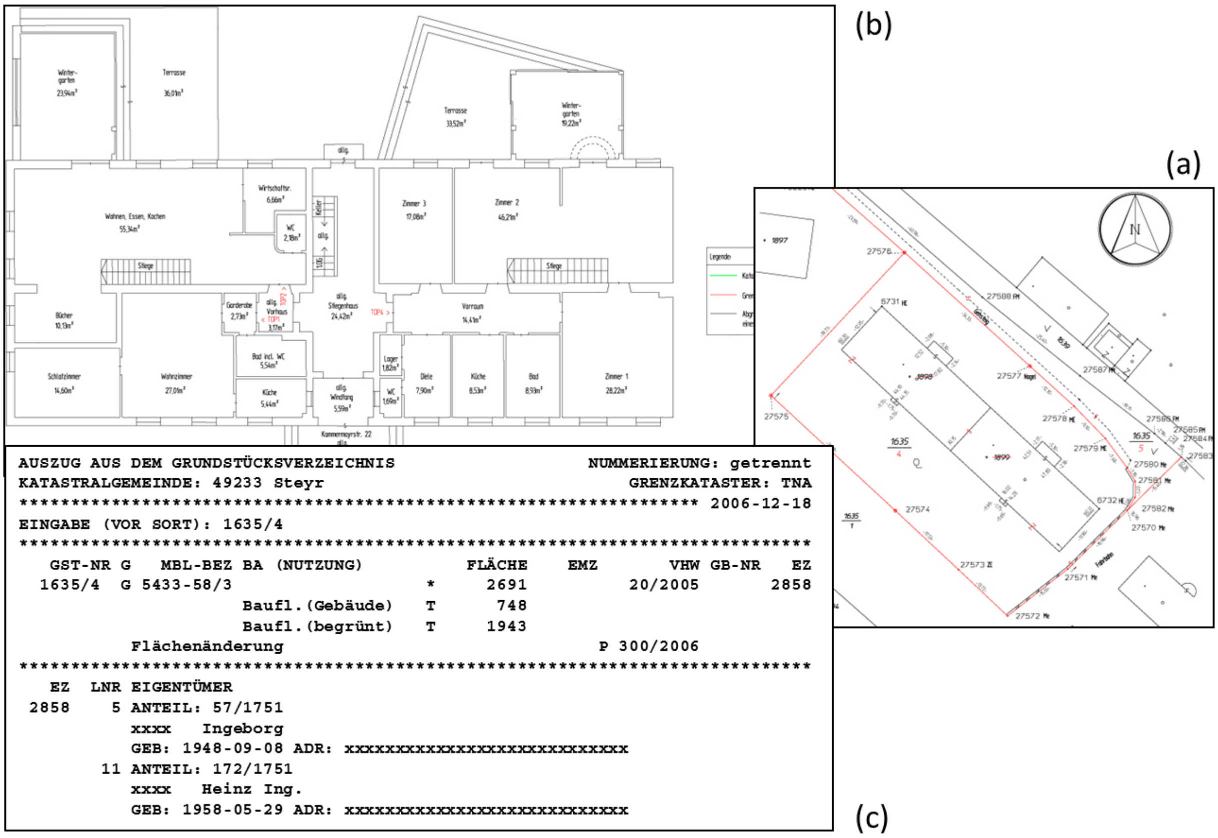


Figure 5: Representation of condominium in Austria (Source: Vermessungsbüro DI Mayrhofer)

2.5 Bulgaria

2.5.1 Background information

In the second half of 20th century when Bulgaria was under the totalitarian regime the deed registration system was adopted in 1910 following the Belgium model. The New Bulgarian civil law was built on the foundations laid by the Roman legal system, enshrined in the French Civil Code of 1804, the Italian Civil Code of 1865, but it has also borrowed from the legal systems of other countries. The legal records were kept by central and local agencies. Cadastral mapping was only for mapping purposes primarily in the urban areas. In 1990 in Bulgaria, private rights and liberalized land markets were restored by law. Nearly 90% of the territory of the country was restituted. The development of the digital cadastral system and property register in Bulgaria started in early 90s. The change was initiated with acceptance of the law of ownership and use of land (Penev, 2016). Cadastre and property register act (CPRA) has been established in 2000 and it arranges new principles for the organization, funding, creation, administration and use of the cadastre and the property register. It is intended to serve as a basis for reform in the registration and transfer from personal to property registration. The Act provides for the introduction of information systems for land registers, which are designed to store, maintain and provide cadastral data and property rights. Nowadays in the capital Sofia and some more big cities in the country everything is in digital form and an analogue archive is carefully kept. However digitization and database creation in the smaller ones is still in process.

2.5.2 Status of 3D objects' recording

Currently only 20% of the country has digital 2D Cadastral systems that is working efficiently. Since the efforts are mainly focused to cover the complete country first with 2D digital cadastre, the third dimension is still not considered of primary importance. However, in the urban environment, mainly in the capital Sofia, there are situations where 3D Cadastre is definitely needed. Most common examples in Bulgaria for situations wrongly registered in the 2D cadastre system are underpasses which are shopping areas. Another example is shown on Figure 6, where according to the cadastral law the bridges are not included in the cadastral map. Only the beginning and the end of such constructions on the ground should be included in the map. However, on the figure the parcels under the bridge are presented in red. However, for their correct association of rights, restrictions and responsibilities the vertical extent of real property rights should be properly defined.

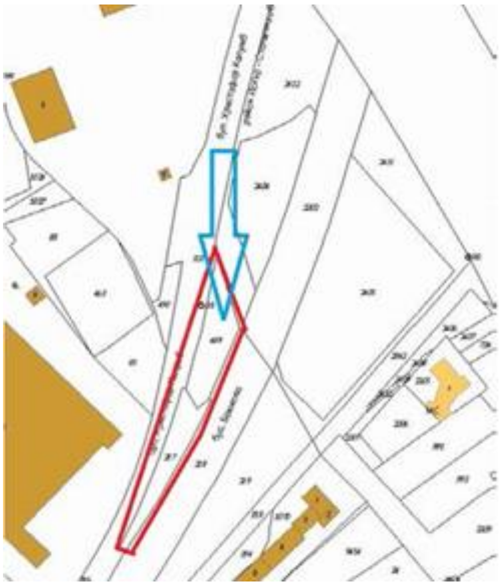


Figure 6: Digital cadastral extract in Bulgaria. (Source: GCCA)

There is no digital 3D registration of underground utilities in Bulgaria. From an institutional and organizational point of view Geodesy, Cartography and Cadastre Agency (GCCA) is an executive agency established in 2001 with main functions pursuant to the Cadastre and property register act. The Agency is a legal entity, having its seat in Sofia and operating through its 28 regional units – Geodesy, Cartography and Cadastre Offices (GCCO), located in the administrative centres of the regions. The cadastre is created, maintained and stored in 2D form by the GCCA and the property register is kept and stored by the Registry Agency. The new Bulgarian system remained deed registration system. The transfer of real property rights takes place with the signature of a deed in front of a private notary. A deed has legal force for municipalities and institutions only upon its compulsory registration in the registry office at court within the day of signature (Evtimov, 2002). The notary must submit it to the judge-registrar. An Integrated Information System for Cadastre and Property Register (IISCPR) was designed to maintain and keep the cadastre and property register up to date. Property Register is kept by the Registry Agency under the Minister of Justice. Minister of Justice exercises direction and control of overall activities in connection with the Land Registry. Cadastre and Land registers are public in Bulgaria. The connection between the two organizations is based on a specially created unique identifier for each immovable property. Using this identifier daily exchange of information is done. The everyday users of Cadastre and Property register are the employees of the organizations, notaries, geodetic and surveying companies, government and municipal institutions, private companies and citizens. According to the law in Bulgarian cadastral system there are registered land properties (defined by right of ownership), buildings and self-constrained objects (SCO) in a building or in a facility of the technical infrastructure (apartments, offices, studios, garages etc.), as presented on Figure 7.

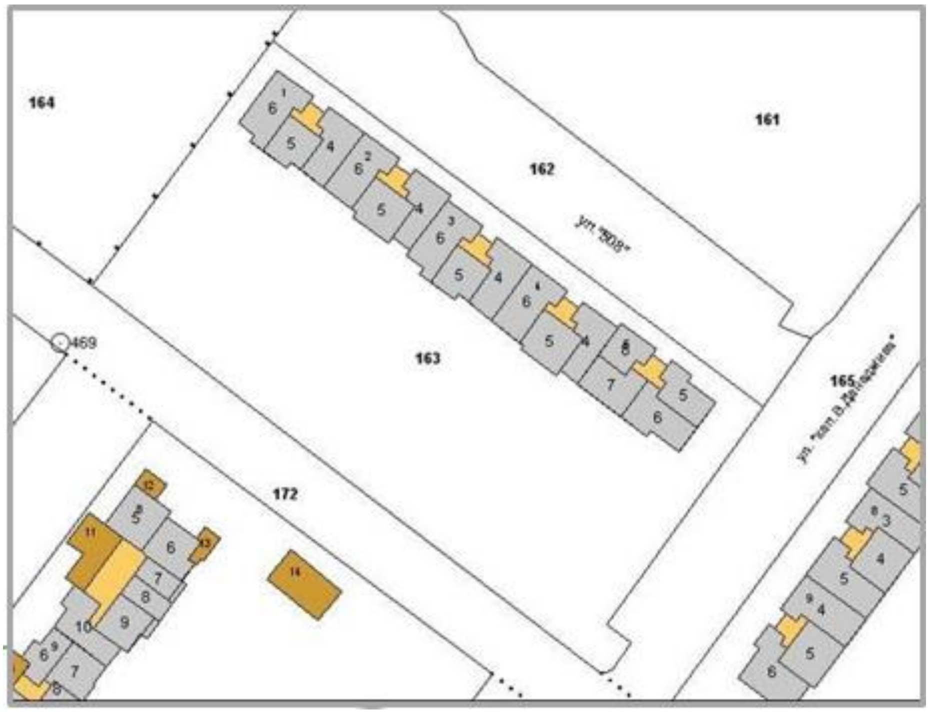


Figure 7: SCO in Bulgarian cadastral system. Source: Digital cadastre in Geodesy, Cartography and Cadastre Agency (GCCA) Bulgaria

2.5.3 Legal definition of 3D objects

In Bulgaria currently there is no accurately described and accepted definition of what is considered as a 3D Cadastral object. Although there are numerous situations especially in the high density areas which require proper registration in terms of height, there has been no progress in terms of 3D Cadastre Legislation.

2.5.4 Concluding remarks

Nowadays in Bulgaria land features are still registered in 2D even when there are proven situations where 3D is needed. As first steps for 3D Cadastre in Bulgaria the 3D architectural plans and 3D models such as BIMs can be considered, which are accepted in Municipalities daily. However, in the current system they are considered as supplementary material or additional source of information due to the fact that in the law third dimension is not mentioned. However, with their help a hybrid version of a 3D Cadastre as defined by Stoter and Salzmann (2003) can be easily applied if allowed in the law.

2.6 Canada (Province of Quebec)

2.6.1 Background information

The province of Quebec (Qc) is one out of 10 provinces in Canada. Its population is about 8.2 million people for an area of 1.7 million of square km (making it the largest Canadian province). Common law prevails everywhere in Canada, except in Quebec, where civil law predominates (Roman Law and Customs of Paris). A first Civil Code of Lower Canada has been adopted in 1866, then introducing legal provisions on land property, ownership, land right transfer, and land registration. A major revision resulted in 1994 (after a few decades of work) with the new Civil Code of Quebec (CCQ). The CCQ contains more than 3000 articles, with some of them referring to the concept of property of things and land (Book IV) and the publication (by registration) of rights (Book IX). For example, Book IV comprises rules about the kinds of property and its appropriation, the ownership, the modalities of ownership, the dismemberments of the right of ownership (i.e. easements), the restrictions on the free disposition of certain property, the patrimonies by appropriation, and the administration of the property of others. Several laws support the application of the CCQ, like the Act regarding Land Survey, the Cadastre Act, the Act regarding Land Use Planning and Development, the Territorial Division Act, the Act regarding Registry Offices, and the Act to promote the Reform of the Cadastre in Quebec, since they all refer to some aspects of land property management.

The Quebec Land Registry System is not a Torrens system, where each title is guaranteed by the State. Instead, the security of land title depends upon a Deeds Registration System, that indexes and archives legal documents related to rights in land. To constitute the legal title of property of one owner to a piece of land, "a chain of titles" from the original grant of the land by the State to the current individual owner need to be established. Land registry offices were established in Quebec in 1840. It consisted, at that time, of a mere Index of names, in which legal documents were files according to the name of the contracting parties, without a direct connection to a specific piece of land. That structure was not fully effective to secure land rights. To resolve the problem, a cadastre was legally created in 1860: since then, all legal documents were able to be filed according to each land lot number, and registered in a land book. For more than a century, the cadastral map became gradually obsolete because of a weak update procedure: new parcels were not systematically represented graphically and identified with an individual lot number. In 1994, an important cadastral reform was launched, aimed at renewing all cadastral plans and producing one accurate, digital, online, and up-to-date cadastre and registration system.

The official authority responsible for managing the land registration system is the Ministry of Energy and Natural Resources (MERN). Composed either by the land book and the cadastral map, the land registry is accessible online[1] where all cadastral plans, land books and legal documents are available, and updated each day. In 2017, more than 4.0 million of private land parcels were recorded in the renewed Quebec cadastral system (3.48 million of land parcel and 549 000 of vertical lot). This one can also be defined as multi-purpose, because it is also used as the basis for fiscal and land use regulation purposes, such as those proposed by local municipalities. Cadastral data also assist in the establishment of land administrative boundaries (as territorial subdivision). Otherwise, it is mainly used by notaries, lawyers and land-surveyors.

[1] The official Real Estate Registers are available on https://www.registrefoncier.gouv.qc.ca/Sirf, while the cadastre maps are available on https://infolot.mern.gouv.qc.ca/.

2.6.2 Status of 3D objects' recording

In CCQ's sections 2972.1 and 2972.2, two mechanisms for registering property rights can be identified. The first one, namely the Land Registry System, corresponds to land books and cadastral plans used to record and publish property information related to land parcels, condominium apartments (vertical cadastre), or any immovable objects located in a 3D space that the owner wants to register. The cadastral map contains the official legal unit number (i.e. lot number), its relative position, dimensions, and area. Easements are not represented on the cadastral map. If a vertical cadastral representation is necessary to identify the co-ownership of condominium apartments, then a specific protocol (technical specifications) to spatially represent these objects is compulsory. It consists of producing supplementary plans (*plan complémentaire-PC* in French) for which subdivision plans and vertical profiles of each distinct lot (whether they are common or individual properties), and showing 3D characteristics (altitude, height and volume information). Figures 8 and 9 show an excerpt of the cadastral map and its corresponding PC plan (Pouliot et al., 2011). The declaration of co-ownership signed by the owners' corporation of the condominium units will then refer to those PC-plans.

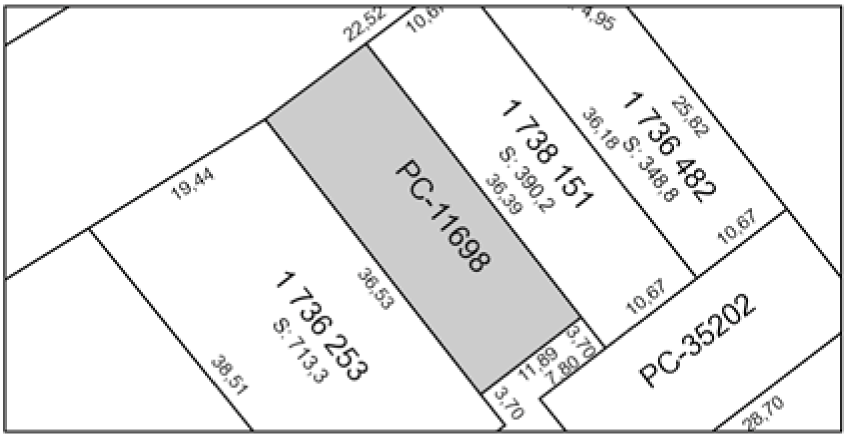


Figure 8: Cadastral plan of overlapping properties marked as PC-11698

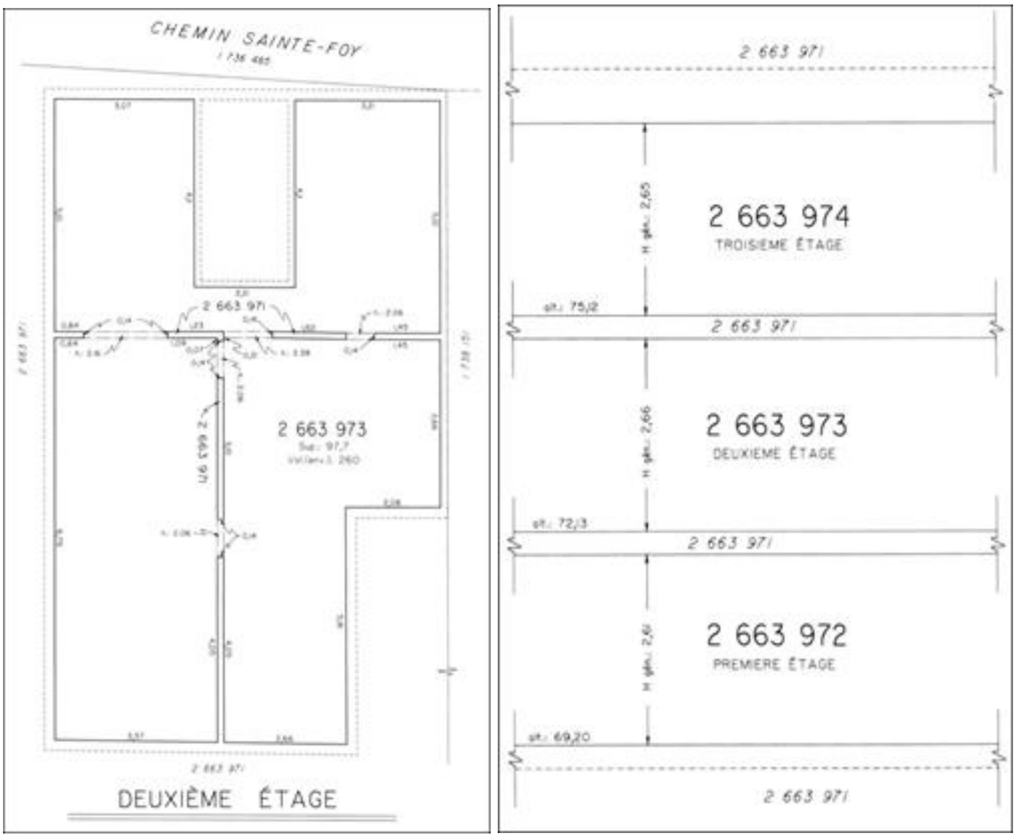


Figure 9: Supplementary plan of PC-11698. (Left: subdivision plan of the second floor. Right: Vertical profile)

The second mechanism refers to property objects that are not distinctly matriculated, like state resources and private utilities networks. This registration system is based on land files that are kept under an ordered number (and not the lot number) and is commonly called FITNO (*Fiches Immobilières Tenues sous un Numéro d'Ordre*). FITNO system proposes two registers as the register of real rights of the State resources and the register of public service networks and immovable objects located in a non-cadastral surveyed territory. These registers maintain a list of real estate transactions (e.g. deed, easement, sale) associated to the legal objects, the name of the holder, the name of regional administration and an ordered number to record the file. In most case, FITNO registration system does not propose spatial representation equivalent to a cadastral plan (Pouliot et al., 2015); there is no mandatory link between FITNO registers and cadastre register.

2.6.3 Legal definition of 3D objects

The Quebec legislation does not refer specifically to the concept of 3D objects. Nevertheless, 3D objects exist and their registration is done through the process previously explained (cadastre system or FITNO). The CCQ refers to land property objects, but no indication is provided about the third dimension. CCQ's section 3026 identifies relative position, the length of boundaries and the unit area. Boundaries are mapped using X and Y coordinates, but these have no legal significance. Beyond legal and descriptive information as name or title, only measurements as length, perimeter and volume have official geometric meaning. PC plans also supply altitude-Z, height and volume of buildings or infrastructures. Consequently, 3D objects can be identified and located according to PC plan documentation. That 3D information is available for cadastral object registration, not for FITNO object registration (except when engineering plans are available, but this is still rare).

2.6.4 Types of rights that can be registered in 3D

The Quebec Land Registry System offers:

- Horizontal ownership (this right is 2D)
- Vertical ownership (mainly co-ownership)
- Easement
- Right of long lease
- Right of superficies
- Mining right

2.6.5 Concluding remarks

Co-ownership was introduced in 1969 in the Civil Code as a new modality of land property tenure. Since that moment, it was possible to identify on supplementary cadastral plans overlapping properties with 3D characteristics. Then, Quebec cadastral system manages 3D situation when overlapping properties exist with 2D map and vertical profiles available on PC plans. Quebec authority is not currently exploring the introduction of full volumetric representations for cadastral data.

Pouliot et al. (2011; 2015) and Pouliot and Girard (2016) investigated the possibility of having volumetric representation for condominium units, and the requirement of having normalised spatial representation for the registration of underground networks or FITNO registers. They highlighted some weaknesses of the current Quebec cadastral system as the challenges for understanding the spatial arrangements of cadastral units. While many PC plans exist, the loose coupling of PC plans with the cadastral database; not having spatial representation for FITNO registration; not being able to know which land parcels are crossing underground network and thus no link with the cadastral system; no guideline for the description of the network (neither semantic or geometric); and the complexity for finding a specific underground network in the current registration system are some of the issues. Pouliot and Girard (2016) support the mandatory registration and mapping of underground utility networks, which will be accessible by all concerned (the owners, the public administration, the land lawyer, the notary, the land surveyor, etc.). A new federal Canadian legislation (BILL S-229, an Act enacting the Underground Infrastructure Safety Enhancement) is under preparation which may be foreseen as a step in this direction, although it is devoted to safety enhancements and not necessarily the protection of ownership rights. Besides, MERN is questioning the migration of FITNO records to cadastral unit registration and the value of mapping easements on the cadastre plans.

2.7 China

2.7.1 Background information

China is located on a vast territory of 9.6 million square kilometres. In general, mountain, plateau, and hill occupy almost 69% of Chinese land while and flat land is only 31%. Rural land is 94.7% with its population 53.4% (CBS 2012), the rest is urban land. Although the rural land covers the greatest land area, the percentage of arable land is merely 10.4% which is 1.432

billion Mu (1Mu = 1/15 hectare[2]). The relation between land and people is controversial. On the one hand, people need arable land to supply food. However, the protection of arable land is not sufficient as the quick change of landscape due to urbanization leads to encroachment of farmland as well as farmland's misuse. Land boundaries, as well as land registration, are not updated with the quick change of land rights. Meanwhile, the urban land exemplifies diverse use types comparing to rural land. The typical characteristic is high density and mixed land use, which requires updated land registration system as well as accurate property rights for high-rise development.

There has been a trend of cadastre unification regarding the urban and rural cadastral systems, particularly regarding the emphasis of rural cadastral registration promoted by Opinions on the Registration and Verification of Rural Collective Land (2011). The emerging trend also can be observed in the process of legislation with regard to housing and land registration. For example, the registration acts, Housing Registration Act (2008) and Land Registration Act (2008), have gradually merged to Real estate registration regulation (2015), which confirms the trend of integration of spatial dimension of housing and the land parcel in the cadastral system. Meanwhile, urban cadastre improves in tandem with high-rise development, which is promoted by the Property Law (2007), particularly in regard to independent registration of 3D parcel.

Current research in 3D cadastre in China involves 3D cadastre modelling and data processing, spatial data model and modelling method, topology building algorithm, the design of the 3D cadastral system and its local application such as in Shanghai, Shenzhen, and Xiamen. Conducted research projected the technological development of 3D Cadastre in China and the practical need of 3D cadastre in local practice.

However, research also reflected that it is difficult for 3D cadastre model to be applied in China due to several reasons. Firstly, complex land use types, as well as mixture of rural land and urban land problems, as it is hard to establish unified 3D cadastre information system for the whole country. Secondly, pilot projects for 3D cadastre implementation in urban areas of China such as Shenzhen, Wuhan, and Shanghai are being undertaken. The demand for high-quality cadastre information for property registration and transaction has been on the agenda since high-rise real property boom in cities. But barriers regarding the implementation of 3D cadastre exist mainly due to the uneven land administration structure. The two issues mentioned above increase the difficulties regarding the unified cadastre system as well as the improvement of 3D cadastre in China.

2.7.2 Status of 3D objects' recording

Recent progress towards 3D cadastre development in practice is especially prominent in several cities in China. Shenzhen Planning and Land Development Research Centre led a research project on "key technology and normative research of land space and use right management." The research centre designed a unified model of two/three-dimensional map management, verified the necessary and sufficient conditions for the automatic construction of three-dimensional topological relations, and proposed a search algorithm for 3D topological relations. The problem realizes the dynamic maintenance of three-dimensional topological relations. By solving the technical problem, the project designed the three-dimensional property body coding scheme and the three-dimensional property right certificate scheme, and formulated the "three-dimensional property body surveying and mapping specifications".

[2] http://www.unc.edu/~rowlett/units/dictM.html

The research and demonstration of 3D cadastre have been up to a certain level. Guo et al. (2013) proposed the 3D representation of property by establishing a land volume and building model inside, applied to a case of underground parking space of Nanshan district in Shenzhen. In 2011, Shenzhen auctioned a piece of underground land for parking cars. The surface land is planned as urban green for public use, while another two-storey underground parking space covering 16,000 m2 is designed. The land department listed underground land for auction using the 3D representation model. Meanwhile, the model was recorded and archived as a 3D digital version for underground land administration (Guo, et al. 2013).
Furthermore, Ji (2007) designed 3D cadastral objects registration model (3DCORM) in ArcScene by using cases of Songbai high-rise building and Lujiang underground car park in Xiamen (Ji 2007). Liao (2014) proposed two 3D cadastre models that are closed spatial land parcel and open spatial land parcel and emphasized the importance of 3D land planning and approval process for the implementation of 3D cadastre in Shanghai (Liao 2014).

2.7.3 Legal definition of 3D objects

Cadastre referred to the state for a certain purpose, record of land ownership, boundary, quantity, quality and use of the core situation of the registration book. It has been through a long process regarding the cognition of cadastre in 2D. Even in recent publications, scholars recognized cadastre as a record of land ownership, boundary, quality, quantity and use of the core situation of 2D registration document (Genshen Su, 2011).
The concept of 2D data cadastre was given in Cadastral Investigation Procedure. "Cadastre refers to the record of land ownership, location, quantity, quality, value, use and other essential conditions of the registry book and data". The cadastre has been recognized as 2D for a long time. The most substantial progress regarding legislation of 3D land and property rights is the issue of the Property Law in 2007.
The Property Law (2007) confirms the dual land ownership regarding the State and Collective (Article 47, Article 48). It also mentions the real property registration authority as well as the register as the key legal-proof document for land and property rights (Article 16). Importantly, the Property Law for the first time establishes the legal status of superficies and easements (Article 156), which contributes to the development of potential 3D cadastre and land registry. At the same time, the Property Law defines the property rights on buildings involving differentiated ownership that includes exclusive right referring to the private apartment, common rights referring to common property and common management right relating to membership and voting right (Article 70-83). The article demarcates the differentiated properties in 3D. Particularly, it subdivides the common property from the exclusive property, which forms the basis of 3D cadastre in building level (figure 10). Besides, the article 136 allows the independent registration of 3D parcel concerning the right to use land for constructions. Article 138 specifies that in a contract concerning the right to use land for construction, the content should include the detailed demarcation of the space.
Since the registration authority separated to land and housing due to individual executive land administration and housing management, land registration and housing registration dis-aggregated each other and operated independently. The historical separation resulted in cadastre referring to land parcel and boundary for land administration. The information sharing and communication between land and housing authorities will facilitate housing registration regarding housing rights registration. The absence of 3D cadastre reflected administrative

segregation in a sense. With the high-rise development in urban China, the protection of private property raised the demand on 3D land and property rights registration. Under such background, the definition of the spatial registration object was officially defined by the definition of real property unit in Real Property Registration Operational Specification (2016). Real property registration should be registered as a basic unit of real property. Real property units are spaces where the ownership boundary is closed and has an independent use value. The space for independent use should be sufficient for the proper use and can be utilized independently (figure 11).

Figure 10: Land and building integration in 3D cadastre (Source: Real property rights survey technical program, 2015)

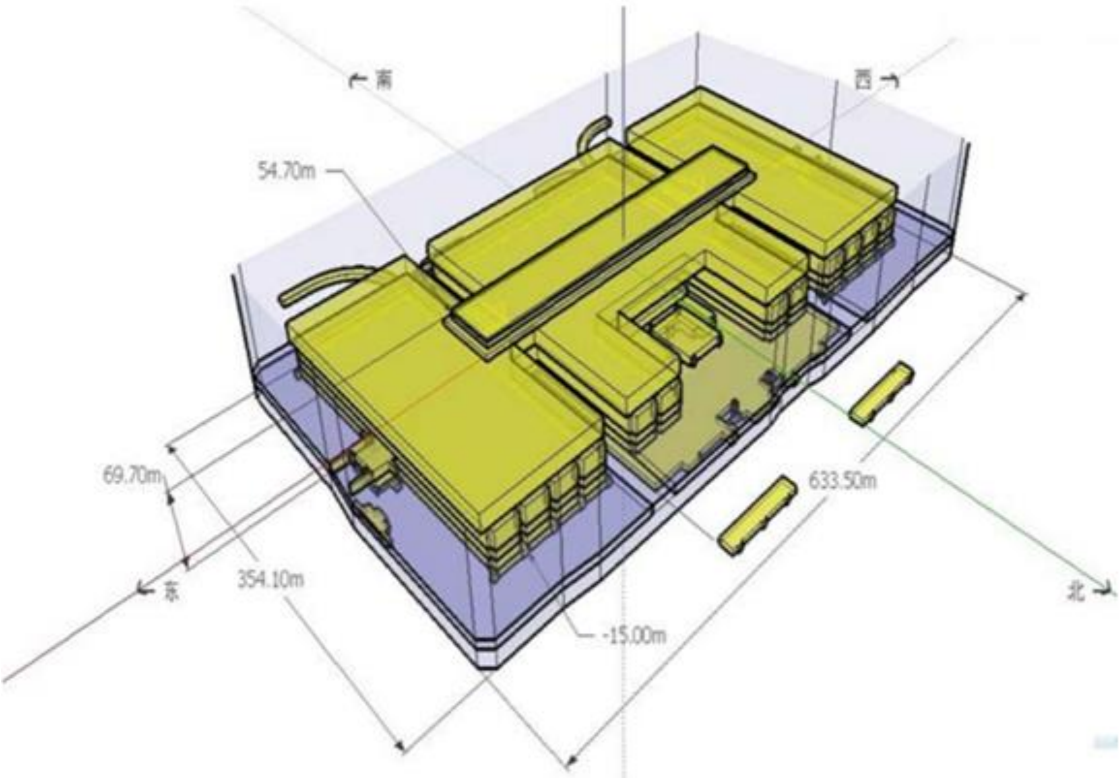


Figure 11: 3D representation in the registration file (Source: Guo et al. 2012)

2.7.4 Types of rights that can be registered in 3D

Provisional Regulations on Real Property Registration (2015) provide that the following real property rights should be registered. (1) Ownership of collective land; (2) ownership of buildings and structures, such as houses; (3) forest ownership; (4) cultivated land, woodland, grassland (5) use rights of construction land; (6) use rights of homestead land (8) easements; (9) mortgage rights and etc. (Article 5). The electronic medium is regarded as the real property register medium (Article 9). The register of real estate shall be kept by the real estate registration institution permanently (Article 13). The competent department of land and resources under the State Council shall in conjunction with the relevant departments establish a unified platform for the registration of information on real estate registration (Article 23).

Furthermore, Real Property Registration Operational Specification (2016) clarifies the record type and method, including registration of collective land ownership, state-owned construction land use right and housing ownership registration, homestead land use rights and housing ownership registration, and collective construction land use rights and buildings, structures ownership registration.

It also defines the registration unit regarding real property registration (Article 1.3.1). The real property should be registered as a basic unit in the registration. Real property units are spaces where the ownership boundary is closed and has an independent use value. The space for independent use should be sufficient for the proper use and can be employed independently.

2.7.5 Concluding remarks

The development of 3D cadastre is a long process in China, which requires addressing two main difficulties. One is the unified land registration system regarding rural and urban land administration. The second one is the inclusive and clarified land administration structure from the central government to local authority regarding vertical organizations as well as horizontal collaborations. However, precise definition of the 3D object is legitimized by regulations in China, which is referred to 3D real property unit. The real property unit is legally bonded by Property Law, which confirms that land right is a bundle of spatial rights, including underground, ground and above ground land use rights, and the land and property conveyance should be bonded as a 3D object in any circumstances. There are also practices of 3D cadastre visualization and monitoring administration in Shenzhen, Wuhan, and Shanghai. Technical progress is leading the way of 3D Cadastre implementation. However, there are still technical difficulties which need to be resolved. Firstly, insufficient land information, particularly the missing underground information leads to difficulties in collecting detailed information for 3D modelling. Secondly, the vertical information of land title regarding elevation, height, and depth is incomplete. Thirdly, cadastral measurements' content and requirements are required to be expanded in 3D.

In the long run, the 3D cadastre implementation needs further input of technical solutions for data acquisition and modelling process. Moreover, further-advanced legalization of 3D cadastre and social integration are also crucial for the widespread use of 3D cadastre.

2.8 Costa Rica

2.8.1 Background information

In Costa Rica, the right to property is a fundamental right protected at the Constitutional level. Its legal structure is delimited by the Civil Code of 1886, the Laws of Urban Planning, Real Property Tax, National Cadastre and additional special regulations. The Civil Code (CC) refers to the concept of property saying: "The property right is not limited to the surface of the earth, but extends by accession to what is on the surface and to what is below. Subject to the exceptions established by law or convention, the owner can make all the constructions or plantations that fit him above, and make underneath all the constructions he deems fit and remove from the excavations all the products that may be given him." (Art. 505)

In this context, there are two essential points related to 3D property, since the Art. 505 explicitly defines that property is not limited to the surface, but extends vertically.

CC recognizes that ownership is not an absolute right, establishing the possibility to constitute limitations and restrictions to the property. In this sense, Art. 292 of the CC states that it is permissible to establish limitations on the property, but they will not be valid for more than ten years, except in the case of beneficiaries under age, in which this term can be extended until the beneficiary turns twenty-five years of age.

This power to limit or restrict the right to property is ratified in art. 383 of the CC, according to which: "Private property on real estate is subject to certain charges or obligations imposed by law in favour of neighbouring properties, or for reasons of public utility." Despite the development of vertical growth, the volumetric definition of property in the Cadastre Law is not evident, still being represented in 2D cadastral maps.

2.8.2 Status of 3D objects' recording

The development of real estate law in Costa Rica happened through different stages, but the main task has been to have a title that reflects the reality in an adequate way. There is a complexity associated with the different types of property developed in the Costa Rican legal system, and in front of this complexity, the 3D property identification system could make a difference.

The ownership in condominium, co-ownership, variants of these or other types of rights, as well as the various limitations or possibilities established in the Costa Rican Civil Code, make limited the current description of the property in Costa Rica. It generated several conflicts at the registry level because there are differences between the reality and the literal description of the property in the title. In this context, 3D identification system of properties could help, however, even when a 3D identification system already exists in some digital cadastres along the country, it is only as an experimental project.

2.8.3 Legal definition of 3D objects

In Costa Rica, there is no legal concept of 3D property. All parcels are defined in 2D in accordance with National Cadastre Law No. 6545, which states: "property is the portion of land registered as a legal unit in the Public Registry or susceptible of being registered, by a number that individualizes it" (Art. 8). Cadastre is defined as: "the representation and graphic and numerical, literal and statistical description of all lands included in the national territory ... (Art. 2)."

The Civil Code establishes the extension of the property right, stating: "it is not limited to the surface of the earth, but extends through the surface and below. With exceptions established by law or convention, the owner can make all the constructions or plantations that consider convenient, and build underground all the necessary constructions... "In cases of condominium ownership, the above shall only apply with the limitations established in the specific law (Art. 505)."

Costa Rican legislation stipulates that the execution and maintenance of the Cadastre is a function of the State and its realization is the exclusive power of the National Cadastre (Art. 2 Law No. 6545).

2.8.4 Types of rights that can be registered in 3D

Horizontal Property: Defined at the Art. 265 of the Civil Code and regulated in the Property Regulatory Law No. 7933/1999. According to framework of this law, each owner shall be the exclusive owner of his or her house, apartment, office, parking lot among others. There are parts that will be considered in co-ownership, parts assigned as common use which belong to all individual owners. Both different figures can be combined.

The operations of buildings or departments subject to the horizontal property regime, are registered in a special section of cadastre, it is a double registration between the mother parcel and the horizontal property parcels, properly related.

The registration of rights in the volume of a building is perfectly possible and clear in the cadastral map of the horizontal properties. The spatial representation of the extension of rights above the roof and below the lower garage does not exist.

Protected Areas: These are the environmental restrictions on private property established in Art. 33 of Forestry Law No. 7174. They are defined as: a) a radius of 100 meters measured horizontally, in the areas bordering permanent springs, b) a strip of 15 meters in a rural area and 10 meters in an urban area, measured horizontally on both sides, on the banks of rivers, streams or streams, if the ground is flat, and 50 meters horizontal if the terrain is broken, and c) an area of 50 meters measured horizontally on the banks of lakes and natural reservoirs and in lakes or artificial reservoirs built by the State and its institutions (except for private artificial lakes and reservoirs). These protected areas prohibit the cutting or removal of trees in the protected areas described, except for declared projects of national convenience (Article 34).

Reservation of public domain in favour of the Nation: Regulated in Art. 31 of Law No. 276 of Water, it comprises the lands that surround the sites of abstraction or outlets of drinking water, in a perimeter of not less than 200 meters' radius and forest areas that protect or must protect the set of lands in which the infiltration of drinking water occurs, as well as those that give rise to watersheds and reservoir margins, springs or permanent course of the same waters. In these areas, the legal regime of public and unavailable goods by the subjects of private law applies.

Easements: Regulated to the Construction Law defines "the restriction of the domain of a property which is established for public benefit or another property" (Art. I.3). Easements cannot be imposed on or in the name of a person, but only in favour of a fund (Art. 370 Civil Code), it is characterized by being inseparable from the fund to which they actively or passively belong (Art. 372 CC) and its indivisibility (Art. 373 CC). The types, lengths and special characteristics are regulated in the Regulation for the National Control of Splits and Urbanizations, No. 3391.

Easements for the use of public waters: Stipulated at Art. 99 et seq. of Water Law No. 276 for the construction of works of public interest in private property.

Easements of high voltage electrical lines (through the air): Costa Rican Institute of Electricity has the power to expropriate and impose forced easement on private property, for reasons of public utility (Art. 2).

Aeronautical Easement Zones: The General Law of Civil Aviation No. 5150 defines the requirements and procedures for conducting aeronautical studies of height restrictions, applicable to the construction and installation of telecommunications infrastructure to be located in the area of influence of an aerodrome, which is defined as the area of land or water (including all buildings, installations and equipment) to be used for the arrival, departure and surface movement of civil aircrafts.

2.8.5 Concluding remarks

The Cadastre and the Property Registry are under the same institution (National Registry) that simplifies the connection of the legal and physical data.
The Civil Code (CC) refers to the concept of property saying: "The property right is not limited to the surface of the earth, but extends by accession to what is on the surface and to what is

below. Subject to the exceptions established by law or convention, the owner can make all the constructions or plantations that fit him above, and make underneath all the constructions he deems fit and remove from the excavations all the products that may be given him." (Art. 505). In this context, there is an essential point related to 3D property: the property is not limited to the surface, but extends vertically.

The CC recognizes that ownership is not an absolute right, establishing the possibility to constitute limitations and restrictions to the property. In this sense, Art. 292 states that it is permissible to establish limitations on the property, but they will not be valid for more than ten years, except in the case of beneficiaries under age, in which this term can be extended until the beneficiary turns twenty-five years of age.

At the level of the cadastral maps, as documents that graphically identify the property in Costa Rica, there is no description of 3D elements. The map registered as a graphic element of the property description contains elements that identify the parcel only at 2D level, however the 3D boundaries in apartments are the structure elements, the exterior walls are common property, and the boundary is the inside of the wall and ceiling (Figure 12).

The development of projects oriented to 3D implementation is moving forward and probably they will be effective soon. Figure 13 shows an example, developed in Escazu city.

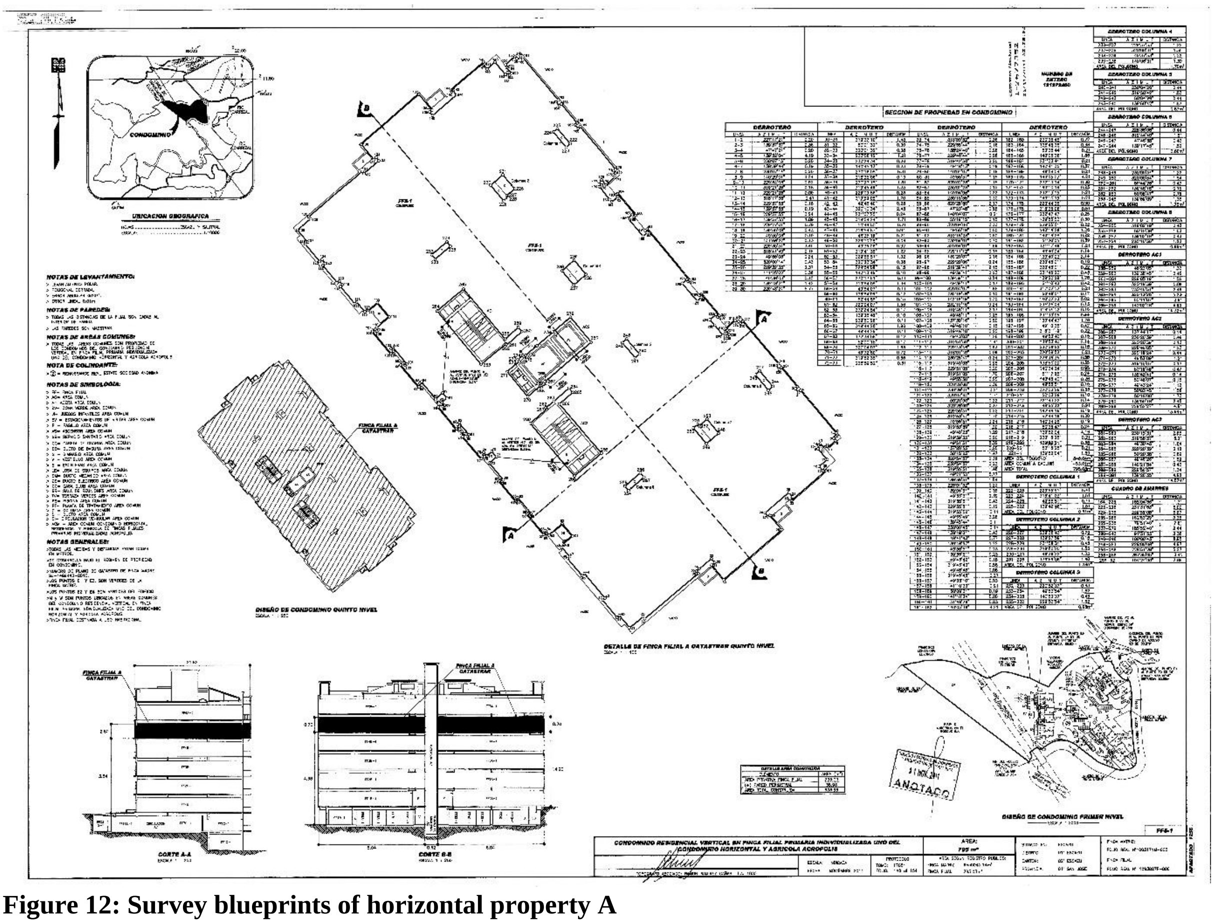


Figure 12: Survey blueprints of horizontal property A

Figure 13: 3D perspective of Escazu - Costa Rica

2.9 Croatia

2.9.1 Background information

Real property in Croatian real property law is, according to the "superficies solo cedit" principle, a land surface parcel to include everything permanently associated with this parcel on or below the land surface (primarily buildings, houses, etc.). A real property, in legal terms, may consist of more land parcels registered in the land book in the same property sheet, as they are hence legally combined in a single body (registered land unit). Grass, trees, fruits and all valuable commodities the land provides on the surface are parts of this real property until this land is divided. What is on the Earth's surface, built on or below the ground with intention to remain there permanently or is built in, added to or on top of the real property, or associated permanently in any other way, and is a part of this real property until partitioned. However, parts of the land of a building and other land associated features with a temporary purpose are not.

2.9.2 Status of 3D objects' recording

Buildings are registered in the cadastre at obligatory request of a party. A geodetic report prepared by the authorized survey company must be supplied with this request. Responsible cadastral office must prior review and certify the report. Buildings are registered in the cadastre with the following attributes: area, intended building use, building name, and house number. On the cadastral map building are shown in planar view. Condition of registration in the cadastre is currently reduced to 2D entry per floor, so it is technically possible to register in cadastre all owners of each part of the building, but only in the alphanumerical part of cadastral record. Currently cadastre is able to accept analogue and digital graphical data about every floor, but it is not an obligation by law. Only the land book has an obligation to accept elaborate on partition of real property. The cadastre has systematic data entry while in the land register entries are in free field form so the apartments and office spaces can be described in more detail (number of rooms and size of the apartment or office space in square meters). Registration of apartments and office spaces in Croatia has been separately operated since 1958 and continuously operated since 1991. It is a kind of 3D registration. Cadastral offices also archived construction documents as a part of geodetic reports.

2.9.3 Legal definition of 3D objects

Rights referring to the use of a limited space will be registered as 2D parcel registered in the cadastre. However, the right registered might refer to a construction or space on several 2D parcels. Basic spatial unit of the real property cadastre is a cadastral parcel. One cadastral parcel is a unit of a cadastral municipality or cadastral region at sea determined by a parcel number and its boundaries. Unique identifier of the cadastral parcel consists of an identification number of the cadastral municipality or cadastral region at sea and the parcel number. Boundaries of the cadastral parcel may be borders or other boundaries defined by legal relations on the land surface.

2.9.4 Types of rights that can be registered in 3D

Types of rights that can be registered in 3D are any type of rights, which can be registered in 2D. According to the Ordinance on Surveying Design (Official Gazette 2014) the integral part of surveying design is a document called Geodetic Situational Draft. A situational draft is made to display position and elevation data on all visible natural and built features of the land surface in the construction area (e.g. buildings and other structures, utility lines with associated facilities, traffic infrastructure, vegetation, water and related objects, relief etc.). Croatian Land Administration System also register 3D cadastral objects related to constructions (buildings, pipelines, tunnels). Infrastructure objects are also registered in 3D (public utility infrastructure). Right of construction in legal terms is equal to the definition of real property.

2.9.5 Concluding remarks

3D descriptions of land features currently are poor in Croatia. Particular parts of real property are registered in 2D plans (Figure. 14) with indication of the floor where they are located. One could consider this as a 2.5D approach. This approach temporarily enables registration of rights in strata, but it does not support changes. Hence, it is necessary to develop the spatial representation component in registration of 3D objects of law. The best solution would be to add 3D data in cadastral plans (Vučić et al., 2011). This would facilitate registration and better description of particular structures such as bridges, tunnels, viaducts, overpasses, underpasses, underground structures, etc.

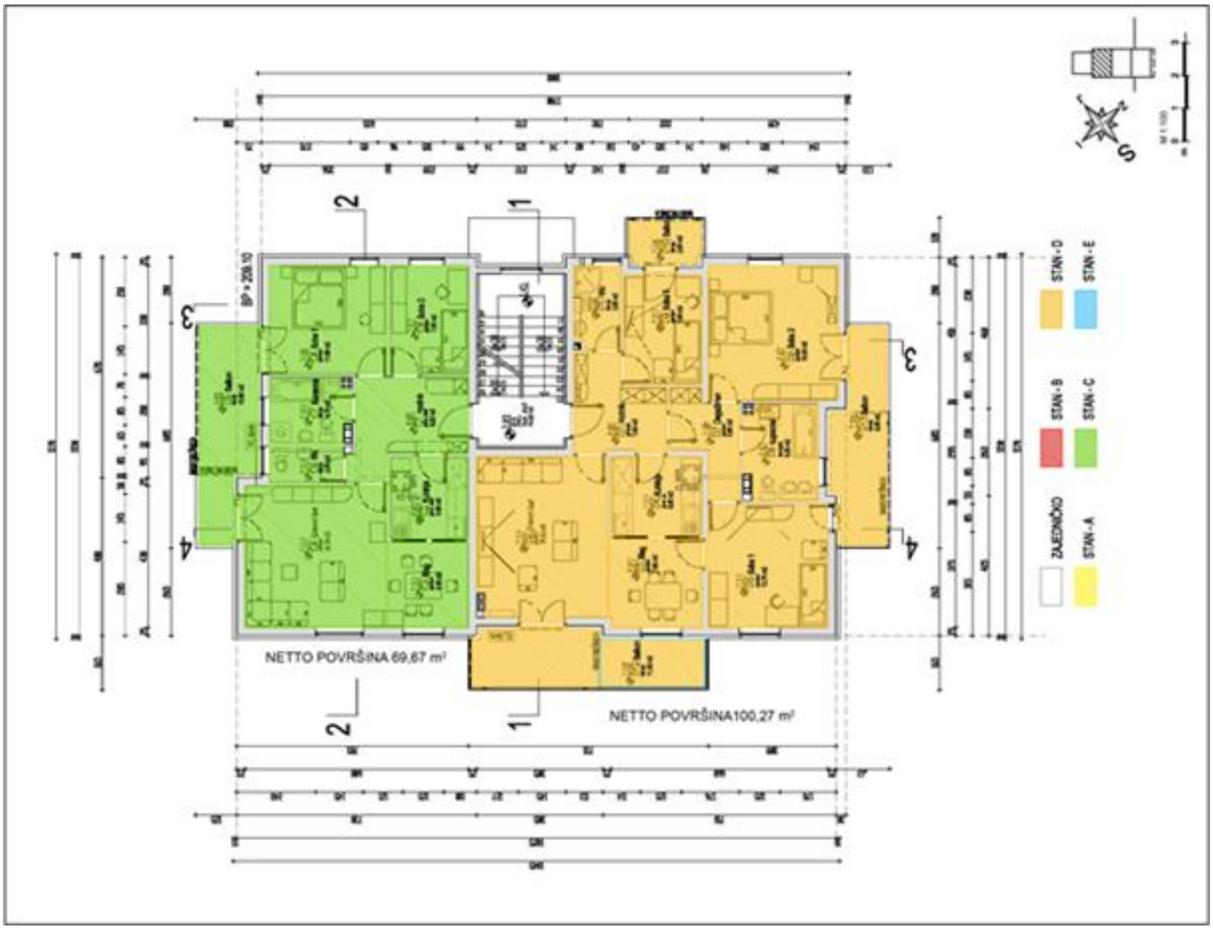


Figure 14: Report on Partition of Real Property (source: URL 1)

In Croatia at this moment there are no official records that can provide complete information about all buildings as spatial objects. Cadastre and Land Book are the only official and systematically maintained registers which contain data on real property, which also includes buildings. Condition, integrity and structure of data collected on buildings and maintained in these registers does not allow insight into the state and basic characteristics of certain buildings and overall condition of buildings in the entire country. Therefore, one of the strategic objectives of the State Geodetic Administration is establishment of multipurpose cadastre of buildings to provide such data and information. Implementation study of the cadastre of buildings should answer how to establish institutional, legislative and financial framework and propose the structure of the data model and technical standard for the information system of such cadastre. Also, this study should provide short-term and long-term strategic guidelines regarding system architecture, data model, specific needs of stakeholders, required legislation, the benefits delivered by such system and financial resources needed for its establishment and maintenance. The study should define implementation phases of the cadastre of buildings based on experiences from EU countries which have already introduced similar systems into daily operations. The study so far, among other activities, questioned the needs of the following future key users: Ministry of Construction and Physical Planning, Tax Administration, Ministry of Justice. It is also in progress questioning the needs these key users: Ministry of the Interior, Croatian Chamber of Economy, National Protection and Rescue Directorate, Croatian Bureau

of Statistics, Croatian Office for the State Property Management, and the representative sample of Croatian cities and municipalities. All of this is conducted to involve public into project and consider the needs of users which will be, after the establishment of the unified multi-purpose register of buildings, an added value to more regular spatial planning, property tax collection, overall development of cities and municipalities, and the overall benefit of the state institutions and society (URL 2).
The plan of the Croatian Government is to create a modern building cadastre that will suit the needs of society and the community.

2.10 Czech Republic

2.10.1 Background information

The Czech cadastral system is based on the compulsory title registration. The cadastre of real estate is the set of data about real estates in the Czech Republic, including their inventory and description and their geometric specification and position. Parts of it are records of property and other material rights and other legally stipulated rights on these real estates. Cadastre of real estate contains many important data about parcels and selected buildings and their owners and is administered as the information system about the territory of the Czech Republic mainly by the computer means, where cadastral unit is the basic territorial unit. Cadastral documentation comprises mainly from the file of geodetic information encompassing the 2D cadastral map (including its digital representation in given cadastral units) and the file of descriptive information including the data about cadastral units, parcels, buildings, flats and non-residential premises, about owners and other justified persons, about legal relations and rights and other facts given by the law. Civil Code defines a real property to be extending to the space above and below the surface parcel, comprising all buildings and constructions permanently attached to it. The real property extent is delimited to the extent that the owner has no reasonable cause in opposing against it or it is subject to laws. The new Civil Code explicitly considers the 3D space above and below the land as a part of the land without any limitation on the maximal height or depth above/below the land. In practise, this can cause trouble. For example, during the construction of tunnels as such constructions affect the space below the land (and this space is a part of the land to "unlimited" depth). Another paragraph of the Civil Code provides that the owner cannot object to activities performed by a third party at a height or depth without justification for preventing such use.

2.10.2 Status of 3D objects' recording

The following types of 3D objects are registered in the Czech cadastre: buildings, residential and non-residential units. The digital cadastral map contains only 2D outlines of buildings and there is no graphical information about the flats in the map. Furthermore, there are 3D objects not registered in the cadastre but schematically displayed on the 2D cadastral map like selected hydraulic structures (dams, weirs and hydroelectric power station) and culverts and bridges. It is possible to register rights on a part of parcel. However, the spatial restriction can only be defined and displayed in 2D.
The underground constructions are not registered in the Czech cadastre and therefore are not displayed in any form on cadastral map. In case that the underground construction is a building with assigned building number, then such underground building can be registered in the Basic Register of Territorial Identification, Addresses and Real Estates (RTIARE). 2D geometries of

such underground buildings are available in RTIARE. This basic register is the central information source for information systems of public authorities (Čada and Janečka, 2016). The examples of such buildings not registered in the cadastre (because they do not have any part above the ground) but registered in the RTIARE can be low energy buildings completely situated below the surface with the roof covered with grass or wine cellars with business premises. The special cases are the underground buildings which are at least partially located above the ground. These buildings are registered in the cadastre and displayed (only outlines of the parts which are located above the ground) on the cadastral map.

2.10.3 Legal definition of 3D objects

The parcels are identified in the cadastre by the number of cadastral territory and parcel number based on an orthogonal projection. The real property could also be the “layers” above or below the ground. Such horizontal division of real property is allowed in a case when particular layers serve for different purposes and are subjects to different legal regime. For example, this is a case of mineral resources, which are owned by the Czech Republic no matter who the owner of the parcel is. On the map, there is no graphical information about these resources and no easements are established.
In case of flats, cadastre does not require volumetric or height data. Only a schematic drawing illustrating the floor plans and textual description of flats is required. Each owner of a flat is also shared owner of common parts of the building. The size of share is determined by the size of his flat in relation to the total area of all flats. The parcel(s) on which the building stands is included in the common parts of the building. The digital cadastral map does not display neither the flat structure nor the spatial distribution of use rights.

2.10.4 Types of rights that can be registered in 3D

Flats: The new Civil Code also regulates the ownership of building units, which was previously contained in a separate act. A building unit remains a separate piece of real estate and does not form part of the land. The owner of the building unit automatically also owns a share of common parts of the building.
The digital cadastral map does not show the apartments and their structure nor the spatial distribution of use rights.

Buildings: After 1 January 2014, a person who owned a building and the land on which it stands, that building became part of the land (the Czech real estate law returned to the principle that structures are part of the land on which they are built - a “superficies solo cedit” principle). Buildings established on land (except for temporary buildings, utility lines and some other exemptions) are no longer be objects of law and only form a part of the land.
If the land owner and the building owner were two different persons during this time, the building remained as real estate, but the land owner holds a pre-emptive right to the building and the building owner holds a pre-emptive right to the land. The building will then become part of the land when the building and the land first meet in the hands of the same owner. The building will not become part of the land if the building or the land is encumbered by a right in rem (i.e. right associated with a property, not based on any personal relationship). The digital cadastral map contains only 2D outlines of buildings.

Before the newly built apartment building and rights are registered to the cadastre, one must provide Cadastral Office with the owner of the building declaration on the limitation of housing units (flat or non-residential premises). A part of this declaration is a schematic drawing illustrating the floor plans and textual description of flats.

Underground constructions: The Civil Code declares that utility constructions, especially water pipelines, sewerage networks or power lines are not a part of land. It is understood that the related constructions and technical facilities are part of utility constructions. To detach the space from land ownership in case of utility constructions the easement is used. The (2D) scope of such easement is then graphically displayed in the digital cadastral map. Underground constructions with separate special-purpose use (e.g. metro, collectors, wine cellars…) are considered as real estates. If an underground construction is not a real estate, then it is a part of the land, even if it affects (lays below) the other land. However, in practice, most of underground constructions are not registered in the cadastre. The special case are the underground buildings which are at least partially located above the ground. These buildings are registered in the cadastre and displayed on the cadastral map, see figures 15 and 16.

Figure 15: (Left) Visualization of the underground construction - the archaeological park in Pavlov, Czech Republic (Olivová, 2016); (Right) Entrance to the archaeological park in Pavlov, Czech Republic (photo: Institute of Archaeology of the CAS, Brno)

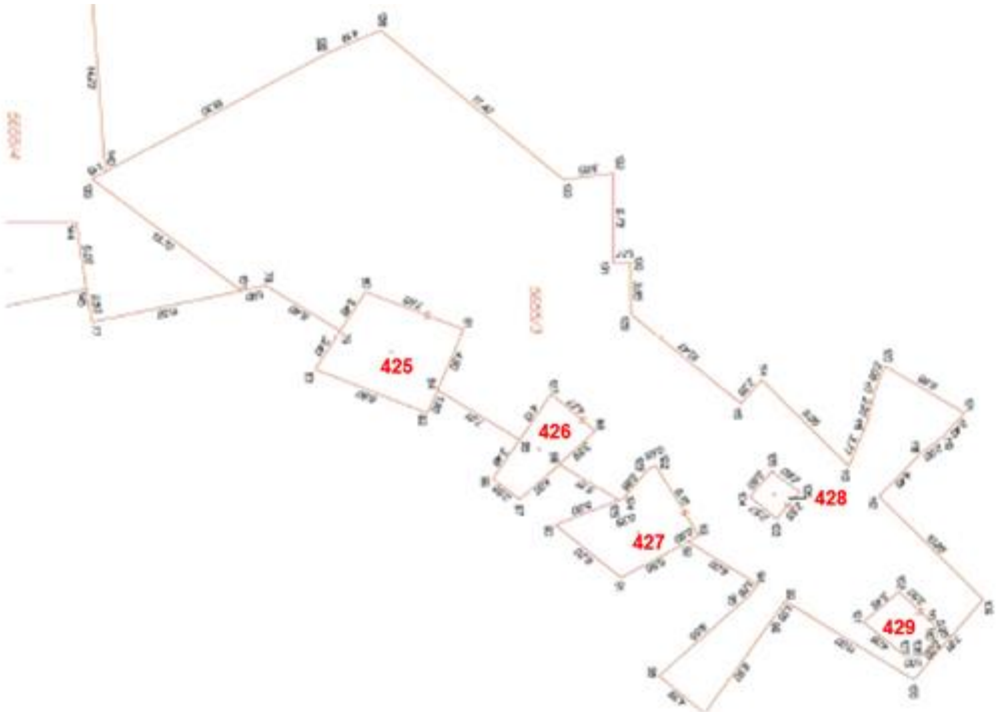


Figure 16: Visualization (in 2D map) of the boundary of the underground construction – the archaeological park in Pavlov. Every part of the construction above the ground must lay on a separate building parcel (here total 5 building parcels with bold red number) (Olivová, (2016).

GeoInfoStrategy and 3D objects: There is a strong emphasis on the creation of National Set of Spatial Objects (NSSO) within the GeoInfoStrategy. NSSO is defined as the source of guaranteed and reference 3D geographic data at the highest possible level of detail for selected objects of the real world, covering the whole territory of the Czech Republic. A part of NSSO should be for example 3D buildings. Within the framework of the GeoInfoStrategy the register of technical infrastructure of public administration containing the utility constructions as 3D objects should be established.

2.10.5 Concluding remarks

The 2D digital cadastral map which covers the whole territory of the Czech Republic is going to be finalized in 2017. In the Czech Republic, the 3D Cadastre is currently mostly academic research which is forced by the needs of professional end-users and the problems their meet in their day-to-day work. On the other side, there is the governmental initiative GeoInfoStrategy (the Strategy for the Development of the Infrastructure for Spatial Information in the Czech Republic to 2020 approved by the Czech government in October 2014) dealing with 3D spatial data and referring also to ISO 19152.

2.11 Greece

2.11.1 Background information

Greece has no established 3D Cadastre legislation and currently there is no indication of introducing so. The country is under cadastral survey due to the ongoing Hellenic Cadastre project in transition from deed registration to title registration system, and further amending of cadastral survey requirements to include more spatial data would increase the project's cost as well as delay its completion (Rokos, 2001). However, there is a significant number of real property objects that can be described as 3D and specific regulations apply. According to Greek legislation immovable property comprises land and its constituent parts (Civil Code, Art. 948). Constituent parts are considered objects that have been steadily attached to the ground, especially buildings […] groundwater […] (Civil Code, Art. 954). Real property ownership extents, if not provided otherwise by law, to the space above and below the earth's surface. However, the owner cannot forbid activities in height or depth that has no interest in opposing against them (Civil Code, Art. 1001), except cases of horizontal ownership (apartment ownership), vertical ownership, mines and regulations imposed by neighbourhood law. Technical requirements of cadastral survey define real property as an "independent and uniform ownership object which is owned in its entirety by one or more co-owners. Real property comprises land parcels, horizontal, vertical and composite vertical ownership, mines and SRPO which have been established in specific regions under customary law."

2.11.2 Status of 3D objects' recording

Although real property objects with 3D characteristics are registered to the Hellenic Cadastre, such as horizontal and vertical ownership, mines, easements and Special Real Property Objects (SRPO), registration is limited on 2D land parcel. In case of underground antiquities or infrastructures, thematic cadastres have been established, e.g. the ongoing Archaeological Cadastre, or data is recorded by the agencies responsible for each utility. Regardless the case, registration and mapping of such objects involves their projection on 2D surface parcels, e.g. utility easements, or identification through tags, e.g. SRPO. On regions where Hellenic Cadastre is operating, registered survey plans include height information, while utilities' operating agencies maintain cross section diagrams, which are also required for granting right of passage through state, municipal, private or public spaces.

2.11.3 Legal definition of 3D objects

Apartment ownership in Greece is called horizontal ownership. Law 3741 "about ownership per floors" establishes ownership of a floor or part of a floor, along with an indivisible share on common property. Cadastral registration does not require submission of volumetric or height data, although building's floor plans and cross sections are planned to be incorporated to the Hellenic Cadastre after completion of the project. Exact location of real property within a building cannot be directly accessed as only buildings' footprints are presented on the cadastral maps.

Vertical ownership allows for separate ownership of a building or buildings within a co-owned land parcel; vertical ownership concept does not imply separate building and land ownership. In case that horizontal property is established within a vertical ownership, this constitutes a composite vertical ownership. Similarly to horizontal ownership, the boundaries of vertical or composite vertical ownership are not shown on the cadastral maps.

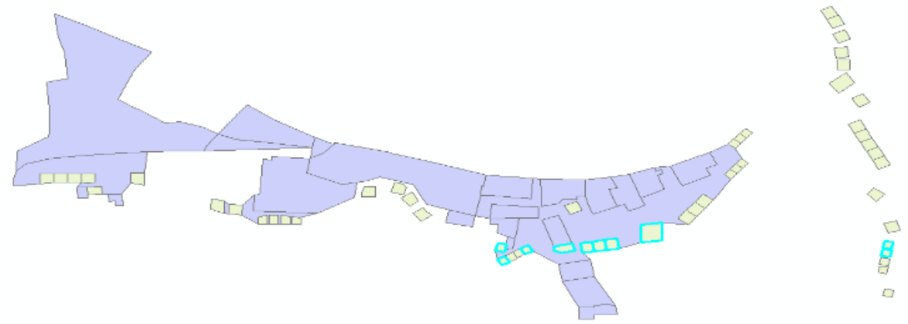
According to Greek Mineral Code, mineral exploration and extraction licenses are granted by the State that requires areas where mineral activities take place to be defined on survey drawings using geographical coordinates in national datum. Article 30 allows for mineral exploration activities on the surface parcel and below in unlimited depth. Mineral activities are registered in Mortgage Register Offices and operating Cadastral Offices under responsibility of the State

(Article 86). Mines' boundaries are maintained on a separate layer to be separated from overlying land parcels.

Similarly, underground pipelines are considered to be of public benefit and are established through servitudes of passage. The law provides for further restrictions on building structures and plantation along pipeline's centre line recorded to local Mortgage Register Offices or operating Cadastral Offices under Ministerial Decrees.

Recording of archaeological sites in Greece is under responsibility of the, currently under construction, 2D "Archaeological Cadastre". However, restrictions and responsibilities of land parcels that fall within regulations of Archaeological legislation are not recorded during this stage of the project.

Other types of 3D property units traced in Greece are SRPO, deriving from Customary Law including "anogeia" (constructions built over another parcel), "katogeia" (constructions built below ground level), "yposkafa" (constructions built below another parcel, usually dug into the earth), "syrmata" (constructions built on the seashore to draw boats during winter), arches (property objects extending over a road), wells and tanks. Registration of SRPO requires data regarding all involved parcels. Tags are used to identify such objects with reference to the unique cadastral identifiers of related parcels. A separate layer is used to present SRPO to the cadastral map either as polygons or as points, as presented in Figure 17.



MINE	START_DATE	TOMENOT	SHAPE_AREA	SHAPE_LEN	perigrafi
0	24/7/2006	290610136	24,243892	19,809925	yposkafa
0	24/7/2006	290610136	8,029931	11,355201	yposkafa
0	24/7/2006	290610136	8,064718	11,376104	yposkafa
0	24/7/2006	290610145	4,000305	8,000305	yposkafa
0	24/7/2006	290610136	7,968354	11,308444	yposkafa
0	24/7/2006	290610136	4,738876	8,762586	yposkafa
0	24/7/2006	290610136	9,198939	12,644578	yposkafa
0	24/7/2006	290610136	3,977315	7,978655	yposkafa
0	24/7/2006	290610136	4,025763	8,02931	
0	24/7/2006	290610145	3,999812	7,999812	yposkafa

Figure 17: Presentation of "yposkafa" on cadastral map (highlighted in blue) and tags on descriptive database (Source: NCMA S.A. National Cadastre and Mapping Agency)

2.11.4 Concluding remarks

Although a significant number of 3D real property situations can be traced in Greece, there has been no progress towards the establishment of 3D Cadastre legislation. Stratification of real property is currently accommodated within 2D legal and cadastral framework, while the effect of the right of superficies is under evaluation due to its recent establishment and limited application field (state owned real property). Current legal and administrative framework can merely address complex situations of real property stratification. Systematic research is conducted on academic level, (Papaefthymiou et al., 2004; Tsiliakou and Dimopoulou, 2011;

Dimopoulou and Elia, 2012; Kitsakis and Dimopoulou, 2014, Kitsakis and Dimopoulou, 2016) on the aspects and implementation of a 3D cadastral concept in Greece. Completion of the Hellenic Cadastre project is anticipated to allow for concentration on legal and administrative reforms to accommodate 3D cadastral issues.

2.12 Jordan

2.12.1 Background information

Jordan has about 1.6 million real properties. The majority of real properties are located in urban areas in the western part of the country, as the eastern part of the country mainly consists of desert. The Jordanian cadastral and land registration system has its roots in the Ottoman cadastre, which was introduced in the middle of the 19th century. The number of real property services and transactions are constantly increasing (an average of one million different transactions annually) and in recent years the value of land has increased dramatically. A property can be owned by one or more person or legal entities in either single or joint ownership. A property consists of one piece of land (parcel). In addition to parcel ownership the Jordanian legislation allows apartment ownership, i.e. ownership of 3D units to serve as apartments/flats, commercial units, etc. This type of property has gained public interest due to increased pressure on land and rising land values, especially in the capital, Amman, and other urban centres.

2.12.2 Status of 3D objects’ recording

The total number of physical buildings containing registered ownership apartments is more than 70,000, and the total number of apartments is more than 480,000. Apartment registration is part of the property registration procedure. The registration of apartments is done by registering the apartment drawing(s) in the national real property register. In order to register an apartment a survey of the apartment´s physical boundaries is required. The physical boundaries are required to be surveyed by a private surveyor and a drawing to be submitted together with the application for registration. One of the required documents is a detailed map of the apartment footprint containing measurements of new or updated apartment building (figure 18). Measurements locating the apartment within the parcel boundaries are also provided on the map (figure 19).

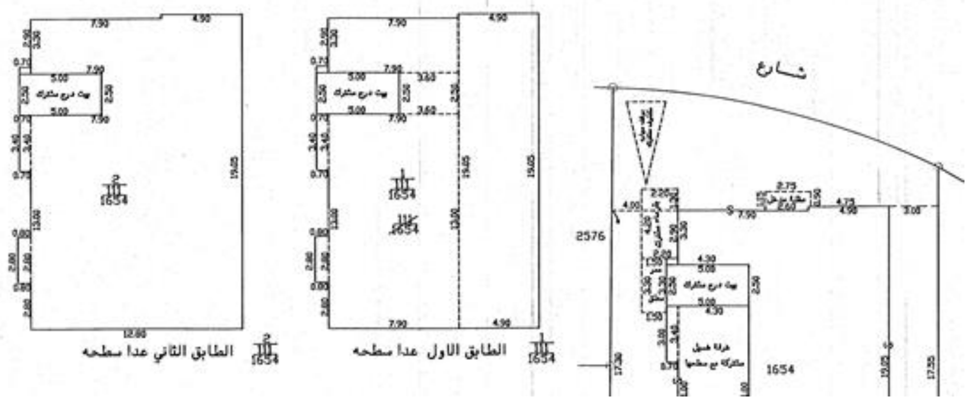


Figure 18: Part of building footprint with detailed apartment measurements (Courtesy of the Department of Lands and Survey, Amman, Jordan)

Since 2016 private surveyors are instructed to supply apartment drawings in digital form as part of the registration procedure. This is done by sending all information about the transaction including a digital file with building data via the Land Registration Directorate to the

Department of Lands and Survey. The apartment building footprints are after verification registered in the cadastral map at the Department of Lands and Survey. A unique building identifier based on the parcel identifier is attached to each apartment. It is planned to register existing 3D units digitally and including them in the cadastral index map by for example scanning the apartment drawings.

Figure 19: Example from the cadastral map database with a new building footprint (yellow polygon) and the Department of Lands and Survey building coordinate (yellow dot). Aerial photo is used as background. (Courtesy of the Department of Lands and Survey, Amman, Jordan)

2.12.3 Legal definition of 3D objects

An apartment is defined as a separate registered object. Each owner has the right to register each apartment built on the parcel as an independent property. The parcel and the parts of the building designated for common use are considered as common ownership for all apartment owners. The land and building parts designated for common use are common for all apartment owners (Law of Ownership of Floors and Apartments of 1968. Law no. 25. With later amendments).

Each apartment has shares in the parcel it is located within. The total number of shares is divided between the apartment owners. If an apartment changes owner it is required that the shares in the parcel follow with the transaction of ownership.

2.12.4 Types of rights that can be registered in 3D

The apartment ownership right is registered in the cadastre. Other rights, restrictions and responsibilities, such as easements and usufructs, are not registered as 3D units.

2.12.5 Concluding remarks

3D property (apartments) is an important component in the Jordanian real property system. The registration of apartments is based on detailed drawings submitted as part of the registration procedures. In addition to this, 2D digital footprints of apartment buildings with a unique identifier for each apartment are also submitted to the registration authorities. The legislation and governmental ordinances for creation and registration of this type of real property has worked well as an instrument to secure ownership for an increasing number of 3D units.

2.13 The Netherlands

2.13.1 Background information

The Netherlands has a proven track record of developing land registry systems which are efficient and widely applicable while also managing to cater to a wide variety of interests. ISO 19152, the Land Administration Domain Model, is an example of this. ISO 19152 and its documentation is written in English however, many documents describing what is happening in the Netherlands are not. The legal base of the Netherlands is the Civil Code (originally from 1838, modernized in 1992). The law system is based on the French Civil Code; however there is an influence from the Roman law and Dutch customary law. In terms of building and land ownership, like in most legal system in other countries, Dutch law adopts the rule taken from Roman law. The most refined system of land registration is title registration where the owner of a certain property will be immediately seen. A deed, drawn by notary in many cases, is the form saying who is giving up rights and who is gaining them and this as for many other countries is presented to the registrar. One of the advantages of deed registration is that the procedure is very quick. In the Netherlands the system consists of three information collections: (1) archive of deeds “public resisters”, (2) parcel-based property register “cadastral register”, and (3) an index map “cadastral map”. All of them are carefully maintained in paper based and nowadays in digital form in the Agency for Cadastre and Public Registers’ ”Cadastre”. The property rights transfer requires notarial deed which has to be registered in the public registers. Each property is identified by a unique parcel number referring to the on in the cadastral map. In the Netherlands according to the law, the ownership of the building and other constructions are included in the ownership of the land. The transfer of ownership takes place after the deed has been registered, and a parcel-based index (cadastral ledger, kadastrale legger) was introduced in the 19th century which has grown into a title register, which fulfils an important role in actual conveyance, but has no special legal status (Zevenbergen, 1996). However, according to the Dutch law it is not possible to divide the ownership of the land into 3D volumes and to convey a building without the land. Using the apartment rights or so called “condominium rights” multi-level properties can still be created. In order to describe the 3D boundaries of properties, the requirements only exist for deeds which establish apartment rights. It is required by the law separate registration per floor in the land registers. Multi-level property rights such as the right of long lease or the right of superficies exist in Netherland before the start of the Dutch Cadastre (in 1832). In the Netherlands the public registers are kept in an analogue form, however the notaries and Kadaster are working in a digital form. The cadastral register has been kept digitally since 1990s. The digitization of the cadastral maps was finished in 1997 and the technical infrastructure has been created in order to allow the notaries to submit the deeds of transfer electronically (Zevenbergen, 2002).

2.13.2 Status of 3D objects recording

The Netherlands is still working on registration of mapping in 3D Legal spaces. The efforts of Kadaster are focused on maintenance and updating of the Large Scale Topographic Map (Basisregistratie Grootschalige Topografie - BGT) which basically includes buildings, roads, water bodies, railways and vegetation. This map is a result of the cooperative work of different organizations such as Municipalities, private companies, Ministry of Industry and Trade, Ministry of Defence and organizations which administer railroads and infrastructure. Current legal system supports the idea that the owner of a property is the owner of the space above and below, however the boundaries are neither visualized nor fixed. The Map of Legal Spaces (Kadastrale Kaart) is a clear example where 3D should be visualised but in reality is still in 2D. For some situations currently, to be efficiently represented 3D ownership situations are projected on a 2D parcel maps. In case that all involved stakeholders agree on multi-level registration in 3D Cadastre the registration will be possible. However challenges can be faced in case of future transfers of multi-level property rights. To address such issues, the Netherlands Kadaster was focused in analysis in order to improve the registration process (Stoter et al. 2012). Therefore two phases for improvement were suggested. The first one, which started in 2012 and finished with a real registration of a 3D situation in 2016, was focused in how to establish rights on 3D volumes for decades and not only to make them visible. These efforts lead to accepting the 3D pdf format as a part of the deed (Figure 20). The second phase which is still in progress deals with 3D data management and dissemination.

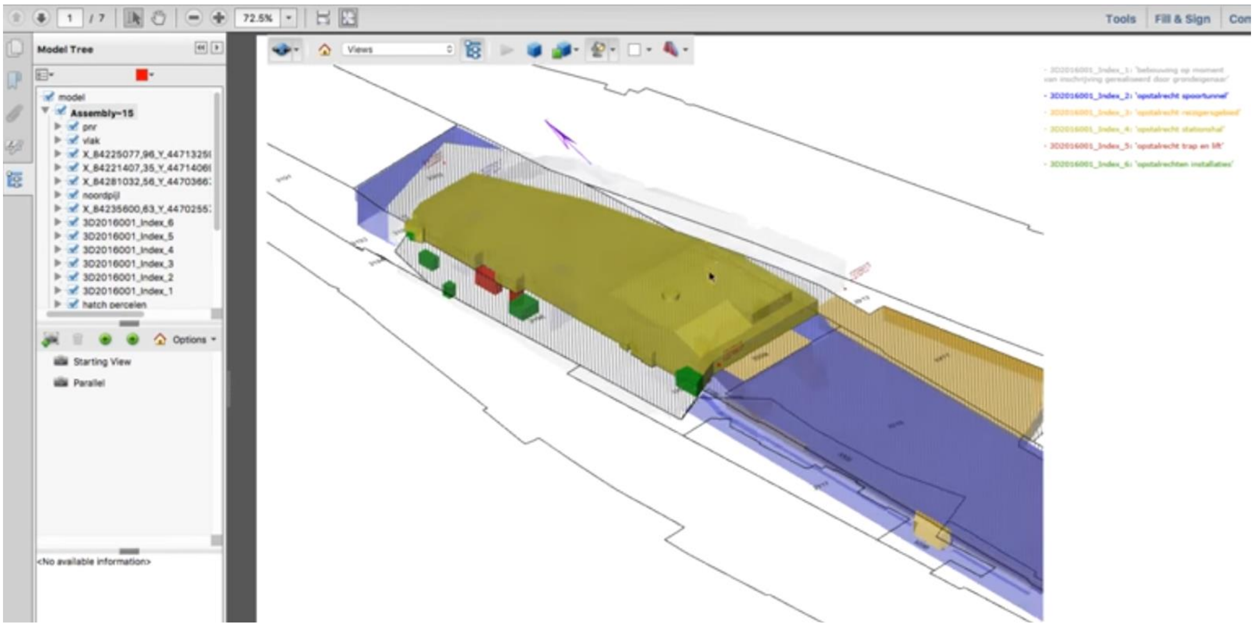


Figure 20: 3D PDF, official document that visualises rights of multi-level ownership in 3D. It concerns the combined city hall and railway station in Delft (Source: https://www.youtube.com/embed/vFMoH-2r7xo)

3D representation of the rights into PDF which was included into the deed was a big achievement reported from Stoter et al. (2016). This deed was also recorded in the Land Register.

2.13.3 Legal definition of 3D objects

It was proved that computer-based model is valid and suitable representation of the real object. With CAD (Computer Aided Design) systems it was found by many researchers in the field that 3D objects can be easily constructed and maintained (v. Oosterom et al., 2005). However for 3D cadastre it's of great importance to consider the difference between 3D objects and 3D parcels. The parcels are not real-world objects. As defined by v. Oosterom et al. (2011) 3D parcels can be considered the legal volumes formed with real rights and that can overlap with several ground parcels.

2.13.4 Concluding remarks

There is no legislation and no legal framework for 3D descriptions of parcels in The Netherlands yet. Netherlands have a lot of official university level research project in cooperation with government bodies and Netherlands is mature for implementation of 3D cadastre legislation. Ideally including 3D in the land registry system definitely is a great step forward. However, it is important to start with initial registration of 3D legal spaces rather than improving the 2D ones. If interactive topological models are created and stored in advance in a spatial 3D database, this would allow better data registration, validation, visualisation and dissemination. Current research is focused on how to lay the groundwork on the legal framework. Stoter et al. (2016) describe how a 3D pdf was registered in the Dutch Kadaster with rights, restrictions and responsibilities in 3D. As described by her this procedure took two years, due to the fact that initially it was registered in 2D and later on upgraded with 3D information. Further development is planned in the direction of 3D registration in Netherlands with a proper modification and adaptation in the regulatory framework.

2.14 Poland

2.14.1 Background information

In Poland, the 2D cadastral system is using 2D parcels in order to register rights to the land. According to the cadastral law in the Polish cadastral system there are three types of cadastral objects that are registered: land parcels, buildings and apartments.

Ownership of apartments in Poland is a kind of 3D registration. Although apartments have 3D characteristics, registration is still based on 2D parcels. Modelling in 3D is not implemented.

Premises registered in the cadastre should be considered as premises defines as (§2 the Cadastral Law) independent dwelling premises or premises of other destination, as understood by the Act of June 24, 1994 on property of premises.

According to the above Act (Article 2), independent dwelling premises is a single room or groups of rooms delineated by permanent walls within a building, which are used for permanent stay of humans, and which – together with auxiliary rooms – are used for meeting dwelling demands of people. This refers, respectively, to independent premises utilised in accordance to their destination, which is other than dwelling needs.

As said in Karabin (2011a), apartments, together with accessory rooms, are marked on projections of appropriate storeys of buildings; in case when accessory rooms are located outside a dwelling building, they are also marked on a copy of cadastral map. The above documents become an annex to an act which establishes a separate ownership of apartment. Those documents are stored in a land book and in a cadastre in analogue form.

According to the regulation of the Ministry of Administration and Digitisation dated October 21, 2015 on the district and the national Geodetic Database of the Technical Facilities (GESUT) – underground tunnels, the subway tunnels and other devices of the underground infrastructure like water, gas pipes etc. are the objects of the GESUT database and they are presented on base maps only. So information concerning those objects may be found on the base maps (scales in towns usually amounts from 1:500 to 1:1000) and in the complete surveying documents concerning those objects in the archive. As said in Karabin (2011b), the content of the base map is sufficient to identify the spatial extension of those objects in the (x, y) plane and for the technical infrastructure installations in the vertical plane as well, since heights of particular elements of that infrastructure (conduits, manholes etc.) are also specified. The technical documentation of subway is stored also in Warsaw's Subway Ltd. Company.

2.14.2 Status of 3D objects' recording

There is no 3D cadastre in Poland. Only some proposals from academic centres exists. Complex model for Poland was worked out by Karabin (2013; 2014). For Poland Karabin (2013; 2014) proposed new cadastral objects, i.e. 2D and 3D parcels, as a result of the proposed registration of the minimum (Z-) and maximum (Z+) levels, which define the vertical extent of property in a metric system. It allows the implementation of a "layer" approach to the rights and restrictions in the cadastre. This idea of a "layer" approach has been presented, among others, by Dimopoulou and Elia (2012) (Figure 21 left).

2.14.3 Legal definition of 3D objects

In the proposal mentioned above performed by Karabin (2013; 2014) new 3D cadastral objects are described for Poland. Karabin (2013) assumed that space should be subdivided into layers: the space accessible by the owner and the space, which will be reserved for the State Treasury - required for security of the aircraft traffic, the space where natural resources occur, below the depth accessible by the private owner. Dimopoulou and Elia (2012) proposed the following division:

- Potential building/constructing space right owned by the State or the Local Authority,
- Potential building/constructing space right owned by the parcel owner/s,
- Existing building owned by the parcel owner/s,
- Parcel owned by one or more private parties,
- Land space under the parcel owned by the State or the Local Authority.

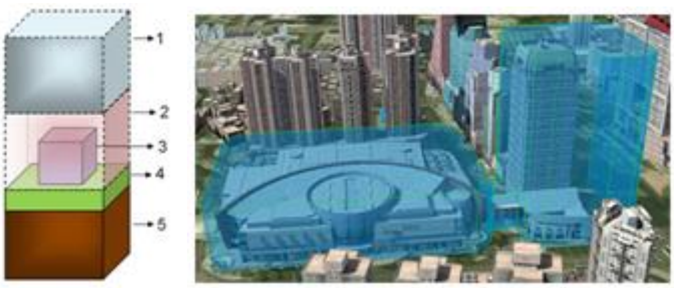


Figure 21: (left) The "layer" approach to the 3D cadastre (Source: Dimopoulou and Elia, 2012), (right) The structures visible in blue - the legal space of the 3D cadastral parcel. Space of construction in the form of a 3D city model (inside the legal space). Source: Ying et al. (2012)

Karabin (2013) proposed a small modification and considered the necessity of registration of the space owned by the State which will never be a subject of private ownership (for example space necessary for assurance of the air traffic, space where natural resources occur, below the depth accessible by the private entity). According to that idea Karabin (2013) proposed new cadastral objects: 2D cadastral parcel and 3D cadastral parcel.

2.14.4 Concluding remarks

First of all, it is necessary to introduce in Poland the division of space of a property. Second necessary step is to register in the cadastre the minimum (Z-) and maximum (Z+) levels, which define the vertical extent of property. It is also important to distinguish between legal space of the 3D cadastral parcel and space of construction. This idea was presented by Ying et al., (2012): "we design two types of cadastral geospace: 3D land space and 3D housing/building space. 3D land space is a certain vertical extension of the 2D parcel according to planning or demands of architecture, and 3D housing/building space is the physical space or its approximation", Figure 21 (right).

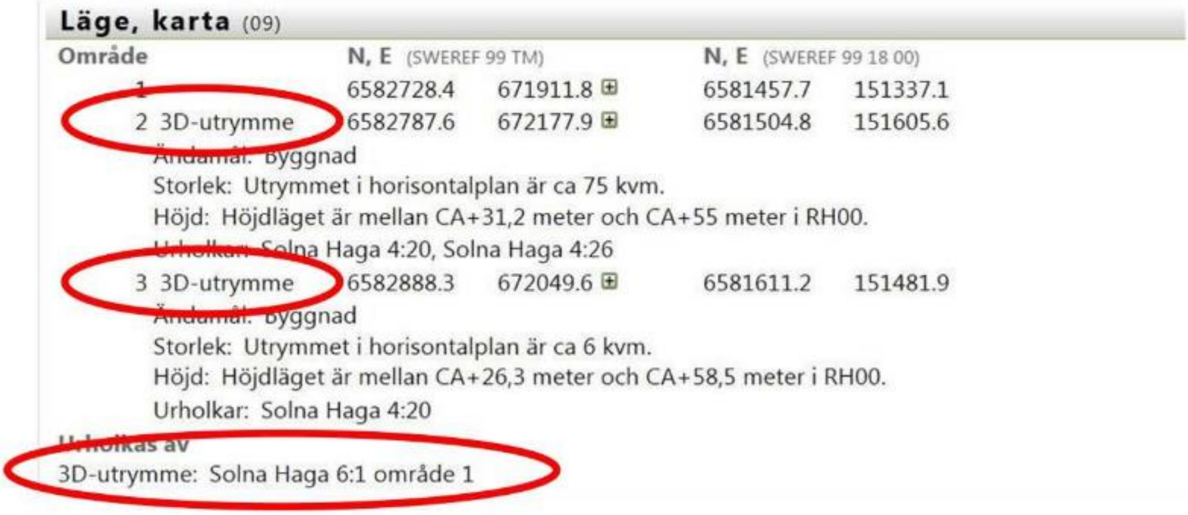
Above guidelines allow to make a first step for introduction of a 3D cadastral system in Poland. Complex model approaches of 3D Cadastre for Poland exists (e.g. Karabin, 2013).

2.15 Sweden

2.15.1 Background information

Sweden is in relation to its size a scarcely populated country. The majority of the population is centred in or in a close distance of the major city centres (Source: Statistics Sweden). This may create complex situations of ownership and other rights, restrictions and responsibilities associated with land (and water and air). One solution to efficiently manage these situations has been the introduction of the concept of 3D property.

All land and, in principle, all water areas are divided into property units or joint property units, which are recorded in the Swedish cadastre, consisting of a textual and a spatial part. The property unit is registered with a unique registration identification number. The physical 2D footprint of a 3D property unit is registered by x and y coordinates in the spatial part of the cadastre, whereas the extension in height can be described in different ways; by z coordinates, by adding a textual description of the legal boundaries in the cadastre (e.g. that they follow the outside of a wall or roof), and the number of the floor level the 3D unit is located on. See examples of 3D registration in Figures 22-24.



Läge, karta (09)

Område	N, E (SWEREF 99 TM)		N, E (SWEREF 99 18 00)	
1	6582728.4	671911.8	6581457.7	151337.1
2 3D-utrymme	6582787.6	672177.9	6581504.8	151605.6

Ändamål: Byggnad
Storlek: Utrymmet i horisontalplan är ca 75 kvm.
Höjd: Höjdläget är mellan CA+31,2 meter och CA+55 meter i RH00.
Urholkar: Solna Haga 4:20, Solna Haga 4:26

3 3D-utrymme	6582888.3	672049.6	6581611.2	151481.9

Ändamål: Byggnad
Storlek: Utrymmet i horisontalplan är ca 6 kvm.
Höjd: Höjdläget är mellan CA+26,3 meter och CA+58,5 meter i RH00.
Urholkar: Solna Haga 4:20

Urholkas av
3D-utrymme: Solna Haga 6:1 område 1

Figure 22: Textual 3D information (in Swedish) in the land register (3D-utrymme = 3D space, i.e. 3D property unit or 3D property space (El-Mekawy et al., 2014)

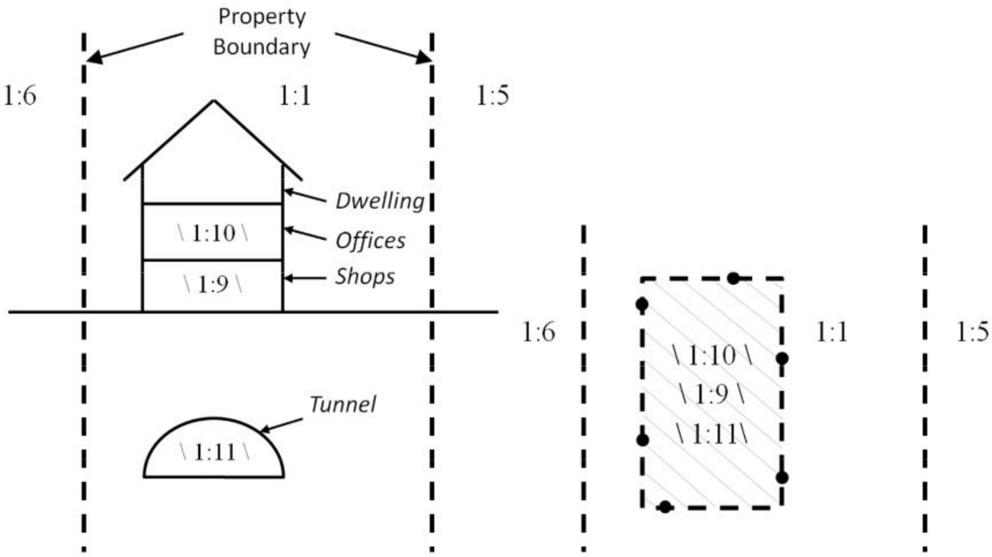


Figure 23: Examples of Swedish 3D property shown in cross section (left) and the visualization on the cadastral index map (right). Based on Lantmäteriet (2004)

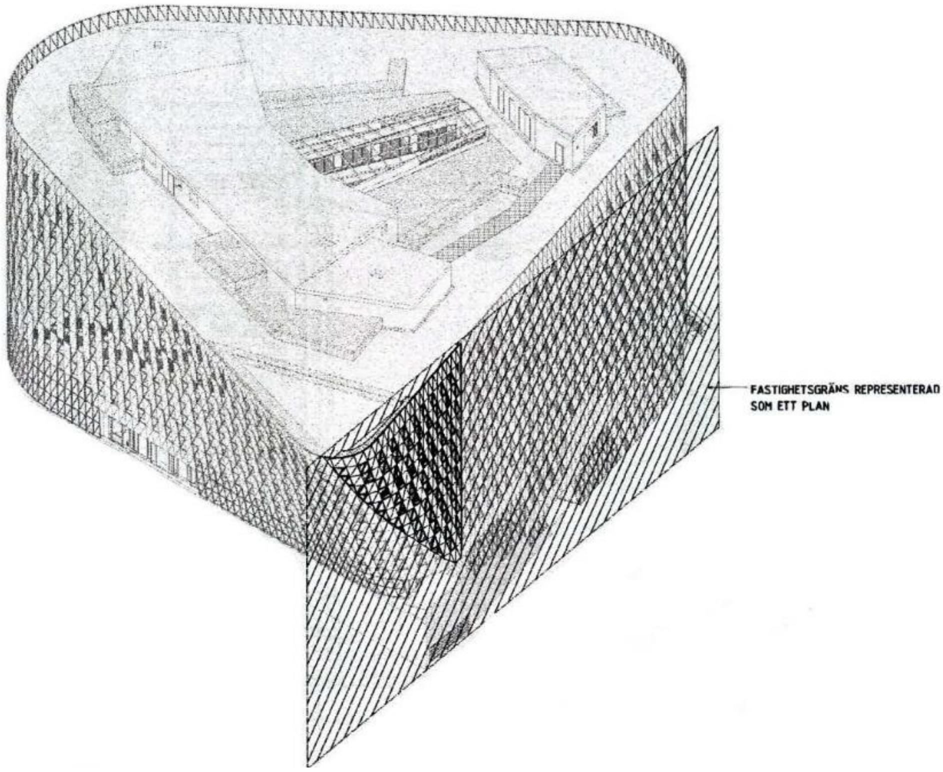


Figure 24: 3D boundary shown as a vertical plane cutting through a building on a 3D construction drawing, being enclosed in the legal survey documents. Based on Lantmäteriet (2014)

2.15.2 Status of 3D objects recording

The concept of 3D property was introduced into the Swedish legislation in 2004 and expanded in 2009 by the addition of condominium (apartment) ownership. The condominium is a special form of 3D property intended for ownership of a residential apartment. For political reasons, it was separated from the initial 3D property legislation and was introduced later. 3D property is, however, still a new instrument for land management. There has been an increase in interest for 3D property and ownership apartments in later years, although the demand has failed to meet the expectations prior to the implementation of the 3D property and condominium legislation (Paasch et al., 2016; El-Mekawy et al., 2014).

2.15.3 Legal definition of 3D objects

3D property is defined as a property unit, which in its entirety is delimited both horizontally and vertically (Swedish Land Code, Chap. 1, Section 1a). It can separate and contain different functions such as units consisting of several apartments or offices, commercial premises, etc. It also often consists of infrastructure objects, e.g. tunnels or other large underground facilities. The 3D unit must relate to a (whole or part of a) built construction or other physical facility (Figure. 22). A Swedish 3D property may extend under or over one or more ground parcels. It is therefore not bound to be located within the boundaries of a 2D property. Condominium apartments are solely created for residential purposes and special conditions and restrictions apply concerning the formation of 3D property (Paulsson, 2012).

2.15.4 Types of rights that can be registered in 3D

There are no limitations on the range of rights related to 3D units. Neither are there any limitations on the range of restrictions or responsibilities related to 3D units. The range of rights to be formed on a 3D property does not differ from those created on 2D property, e.g. ownership, easement/servitude and different types of access and use rights (Paasch et al., 2016, El-Mekawy et al., 2014).

2.15.5 Concluding remarks

Taking into consideration that 3D property formation only has been possible for a little more than a decade the number of 3D properties today is still limited, but the legislation and use of this type of property has worked well and there seems to be an increase in interest to use 3D property formation as an instrument to solve complex ownership and use right issues in urban environments.

3. DISCUSSION AND COMPARISON

The long-term aim of this article was set to contribute to the knowledge base on understanding and developing 3D cadastral systems. Therefore, a short-term objective was targeted to compare and discuss 3D property concepts in selected fifteen countries (or provinces/states) among those which have witnessed some developments in this field in recent years.

To discuss the findings of this article, it is important first to reflect on the definition of the '3D property' concept. It has been found from the compared case studies that there is still inconsistency in the way '3D property' is defined. This conforms to the findings of recent literature reviewed in section 1 that legal aspects in these countries are not yet as developed as the technical aspects (e.g. spatial data infrastructure (SDI), data modelling, database management, and geometrical representation) and the organizational/registration aspects (e.g. management and capacity-building issues, registration of 3D property in land administration systems, such as the content, storage, structure).

The case studies can be summarized as in the tables below.

Table 1: Summary of national case studies

Country	Background information	Status of 3D objects' recording	Legal definition of 3D objects	Rights that can be registered in 3D
Argentina	-Civil law jurisdiction (National and Provincial, hierarchically). - Provincial cadastral system. -Transition from Deeds to Titles in Provincial real property registration system	-2D models with tags (high, levels) -2D registration -Under and above ground utilities are maintained by each Service Company. -Unified real property cadastre in 2D database and thematic cadastre in some cases.	2D (orthogonal projection) and different kind of levels (floor, roof, terrace, subsoil, basement, etc.)	No rights registered in 3D.

	-Land register and cadastre map exist in some cases -Digital form in certain provinces, paper form in others.			
Australia (State of Queensland)	-Common Law -Torrens Title registration system -Paper title not provided to owners -Point of truth for title is Titles Office record, and for dimensions is the paper cadastral plan -Digital cadastral database (DCDB) is a representation only and not the point of truth -Private cadastral surveyors survey land and are legally responsible for accuracy of plan data, State liable for Title -Both Titles Office and Directorate of Survey is within Department of Natural Resources and Mines, but separate offices -DCDB holds 2D with footprint of 3D, currently a project is underway to modify the cadastral databases to accommodate 3D parcels -All cadastral representation, including valuation, topographic data, imagery etc. are open source and is disseminated free of charge	-Building units have been registered under Building Units and Group Titles Act (1980) and Body Corporate and Community Management Act (1997) -2D and 3D Title registered under Land Title Act (1994) for freehold land and Land Act (1994) for crown and non-freehold land, the Surveying and Mapping Infrastructure Act (2003) guides surveyors and geodetic infrastructure, the Surveyors Act (2009) safeguards the public by guiding the surveyors -Directives such as Land Practice Manual, Cadastral Survey Requirements (CSR), and Registrar of Titles Directions for Preparation of Plans (RTDPP) further guide land practitioners	- Separation between 3D Building Format Plan and 3D Volumetric Format plan - Any 3D object can be registered if it can be mathematically defined - Separate legislation exists for 3D Buildings - 3D Volume covered under directives	All rights on 3D are registered, any RRR on 2D is possible to be registered in 3D

Australia (State of Victoria)	-Common law, -Torrens land registration system -Parcel register and index “digital cadastral mapbase” exist -Title register is digital but copies of title are printed in hard copy	-Various 3D (objects) RRRs are registered. -Utility networks are not included in the register -Land Use Victoria is responsible for the title (including cadastral plans) registration, and maintenance of index “digital cadastral mapbase”	Is defined by the type of 3D RRRs and the boundaries that delineate the RRRs	Various 3D RRRs are registered but are represented in 2D diagrams
Austria	-Civil law jurisdiction -National cadastre system - Digital cadastral map and land register - Geometrical basis for condominium stored in land register but not connected to cadastral maps	- 2D registration only - Condominium registration as shared ownership of land - Easements are usually not represented geometrically	N/A (Does not apply)	No rights registered in 3D.
Bulgaria	-Civil law jurisdiction -Deed registration system -The 2D cadastre is maintained by the GCCA and the property register is stored by the Registry Agency. Integrated information system for cadastre and property register (IISCPR) was designed. Cadastre and Land registers are public. - Digital form in the big cities. 20% of the country has digital 2D cadastre.	-2D Cadastre with use of 3D visualisation only for certain objects - under/above ground utilities' recording to Cadastre (YES) -No 3D cadastre legislation -Cadastre is maintained by GCCA and the property register is stored by the Registry Agency.	N/A (Does not apply)	No rights registered in 3D.
Canada (Province of Quebec)	-Civil code jurisdiction -Deeds registration	-Mainly 2D land parcels. -Overlapping properties	The concept of 3D legal object does not exist in the documentation	Co-ownership rights (private and common parts) are described by

	- land register and cadastre map exist -Cadastre reform proposes updated, complete, accurate, digital and online land register and cadastre map.	distinctly indicated on the 2D cadastre plan (with tags) and then refer to subdivision plans, mainly for condominium units. -Registration does not include 3D information but PC plans are available and altitude, height and volume are provided. -Easements are not represented on the 2D cadastral plan. -State resources and distribution networks recorded in distinct registers (not cadastre), no map is available. -Real property cadastre managed by Government.	even though it is possible to register 3D objects (see PC-plans)	altitude and height information in the PC-Plans.
China	-Civil law jurisdiction -Dual cadastre system -Real property title registration system -Land register and cadastre map exist -Digital form in certain cities -Unified cadastre registration under construction, the initial operational status will be achieved by 2018	-2D registration -under/above ground utilities' recording to Cadastre not fulfilled -Not unified registries -Each registry is maintained by responsible institution	Real property unit	3D cadastre in pilot projects
Costa Rica	-Civil Law jurisdiction - Unified national Registry and cadastral system	-2D models with tags (high, levels) -Under and above ground utilities are maintained by each Service Company. -Unified real property cadastre in 2D database and thematic cadastres in some cases.	2D (orthogonal projection) and different kind of levels.	3D cadastre in pilot project

Croatia	- Civil Law jurisdiction - Title, based registration system - Cadastre maps exist in digital form	- use of 3D models in 3D objects' registration (2D models with tags - 2.5D) - under/above ground utilities' recording to Cadastre - Real property cadastre and thematic utility cadastre are maintained by State Geodetic Administration - Land book maintained by local courts (Ministry of Justice)	Rights referring to use of limited space will be registered in land book on a 2D parcel registered in the cadastre and in the land book.	Various 3D RRRs are registered but are represented in 2D diagrams.
Czech Republic	-Civil Law jurisdiction -No 3D cadastre legislation, long established cadastral system based on 2D parcels. -The Czech cadastral system is based on the compulsory title registration -1993 integration of former Land Registry Book and Cadastre of Land into one register -Since 2014 superficies solo cedit principle. -Digital cadastral map for most of the territory of the Czech Republic	-2D registration only -No graphical information about the flats in the map -The underground constructions are not registered in the Czech cadastre and therefore are not displayed in any form on cadastral map. -It is possible to register rights on a part of parcel. The spatial restriction can only be defined and displayed in 2D. -Czech Office for Surveying, Mapping and Cadastre (national mapping agency)	N/A (Does not apply)	No rights registered in 3D.
Greece	-Civil Law jurisdiction -Transition from Deeds to Titles registration system - unified land registry and cadastral map (after completion of	-2D representation of 3D objects to cadastral map using tags and separate thematic layers -projections of servitudes on	N/A (Does not apply)	No rights registered in 3D.

	Hellenic Cadastre project) - Digital (in regions where Hellenic Cadastre is completed)	surface parcels registered -Hellenic Cadastre and thematic cadastres exist -NCMA, agencies responsible for utilities or thematic objects		
Jordan	-Civil Law jurisdiction. -Cadastral legislation has its roots in the Ottoman cadastre. -Digital land registry and cadastral map. -3D cadastral legislation for apartment registration.	-2D registration of 3D objects. -National, digital cadastre and building register exist. -Apartment buildings and 2D layout of apartments are registered as part of the cadastral procedure.	Ownership apartments are defined as separate entities	No rights registered in 3D.
The Netherlands	-Civil Law jurisdiction -Deed registration system -Archive of deeds, parcel-property register and index "cadastral map" are maintained from the Agency for Cadastre and Public Registers -The public registers are kept in an analogue form, notaries and Kadaster are working in a digital form.	-2D registration with the first one fully 3D registration in 2016. No legal framework for 3D descriptions of parcels -2D registration under/above ground utilities' recording to cadastre - Agency for Cadastre and Public Registers "Cadastre" are responsible for the maintenance of the archive of deeds, parcel-property register and index "cadastral map"	3D parcels can be considered the legal volumes formed with real rights and that can overlap with several ground parcels. (v. Oosterom et al., 2011)	Accepted 3D pdf format as a part of the deed - 2016
Poland	-Civil Law jurisdiction -Title registration system -Dual cadastral system (both land register and real estate cadastre exist)	-2D registration only. -Apartment ownership is a kind of 3D registration. Apartments are defined as separate cadastral objects.	N/A (Does not apply)	No rights registered in 3D

	-Land register fully digitalized with one central database Real estate cadastre also in digital form but there is no central database, also divided into two components (cadastral maps and descriptive part of cadastre) -Apartments, together with accessory rooms, are marked on projections of appropriate storeys of buildings and are stored in a land book and in a cadastre in analogue form (not connected to cadastral maps)	-Underground tunnels, the subway tunnels and other devices of the underground infrastructure like water, gas pipes etc. are the objects of the GESUT database (under creation) and they are presented on base maps only (base maps already exists). -Owners of each utility networks have their own databases. -"layers" approach was proposed for Polish 3D Cadastre by academic society		
Sweden	-Civil Law jurisdiction -Titles registration system - unified land registry and cadastral map - Digital - Complex RRRs on real property	-3D Cadastre legislation since 2004 – Condominium legislation established since 2009 - 2D representation of 3D objects to cadastral map - 2D registration - under/above ground utilities' recording to cadastre	3D property is defined as a property unit which in its entirety is delimited both horizontally and vertically (Swedish Land Code, Chap. 1, Section 1a).	No difference with 2D real property – No limitations in 3D RRRs

Table 1 summarises the results of the examined case studies. Despite their Civil Law origins, except for Common Law based state of Queensland and Victoria in Australia, each country is based on a different background reflecting both conceptual differences in real property registration along with different levels of cadastral infrastructure. This includes long lasting cadastral systems, e.g. Austria, to the ongoing Hellenic Cadastre project, and centralised systems that are managed at municipal level. However, all of the examined countries share a number of, different in each case, 3D real property objects that can be efficiently managed by establishing 3D cadastre legislation.

Background: Background research among the examined case studies, presents significant differentiations between each case, which result in differentiations to the focus of each national legal framework and cadastral system as well as its “level of preparation” to accommodate 3D objects’ establishment and registration.
Austrian, Czech and Bulgarian Cadastre currently focus on completing digitisation of their archive and establishment of digital cadastral maps, while in Greece cadastral survey towards the establishment of digital Hellenic Cadastre is still ongoing. In other countries, administrative difficulties such as provincial cadastres or unified registration systems of urban and rural land, e.g. Argentina and China respectively, can be traced, inhibiting progress towards 3D cadastral systems.
On the other hand, the states of Victoria and Queensland in Australia show significant interest within 3D Cadastre field with long-standing legislation for 3D real property combined with research towards the establishment of full 3D cadastral systems, e.g. research towards Victorian 3D digital Cadastre system and initiatives towards 4D registration and 3D indoor navigation and augmented reality in Queensland.

Status: There are highlighted differences in the status. Analysis of examined case studies presents the following types of approaches, although each of these is implemented based on national specifications. Such approaches include:

- Addressing of 3D objects within existing (2D based) legal framework, which is implemented by most of the examined countries (Argentina, Austria, Bulgaria, Czech Republic, Costa Rica, Greece, Poland, Quebec and The Netherlands). However, differentiations ranging from registration of 3D pdf documents, e.g. The Netherlands, or registration of underground structures partially located above ground, e.g. Czech Republic, may apply. Similarly, registration of Greek SRPO under “3D tag” approach constitutes one of the variations within this concept.
- Fully operating 3D cadastral systems as presented in, above mentioned, specific Chinese cities, allowing for 3D partition, registration, representation and management of land (parts of China).
- Addressing of 3D objects within 3D cadastre legislation. This case involves Swedish, Queensland’s and Victorian legislation providing for 3D RRRs. On the other hand, legislative initiative on 3D real property management does not establish mapping of such units in 3D, which results in partial accommodation of 3D objects’ management.
- Registration of immovable objects in 3D space as provided in the province of Quebec, using complementary plans to present buildings’ 3D characteristics. Although this concept does not constitute a complete method of establishing and recording 3D property, since it operates within the, strict under means of real property partition and extent, concept of Civil Law, it allows for a type of 3D partition of space. Even so, it is a concept that is of optional character, while it involves registration of lots’ vertical profiles and 2D cadastral plans. Therefore, it can only be used as a first step towards a 3D cadastral concept. A similar concept, although not optional and focusing on building units, applies to Argentina using 2D plans along with buildings’ cross sections.

It is noted that buildings, and especially apartments, constitute the most common 3D object registered in national Cadastres. Despite their 3D character, such objects are either presented in cadastral maps through their 2D footprint, e.g. buildings, or are not presented at all, while legal documentation on the establishment of apartment units' ownership involves only reference on each unit's floor number.

Legal definition of 3D objects: Conforming to literature findings, it is found in the examined case countries that the lack of clear legislation is shown to have a clear impact on legal definition of 3D objects as well as the registered rights in most of the compared countries. In Sweden, a precise 3D real property definition is used including also residence-purpose-based condominium, while Victoria's legislation also provides for registration of 3D RRRs. The same applies to Queensland, where detailed legislation regulates definition, management and surveying of a wide range of 3D spatial units. On the other hand, legal definitions of spatial units do not apply the 3D terminology in all other countries. In practice, although not established through statutory 3D legal procedure, 3D objects are legally created and managed through layer concepts, based on real property's vertical extent restrictions on Civil Codes, through establishment of servitudes or rights of superficies. Real property objects are registered in 2D as projections to cadastral parcels. 3D characteristics are simplified in 2D restrictions' registration or may even not be presented to the cadastral maps, e.g. Austria, while exceptions such as Chinese 3D cadastral volumes or 3D and volumetric information in Quebec's PC plans along with introduction of 3D drawings in the Netherlands indicate the need of recording, not statutorily established, 3D property. Themed cadastres may also be used, focusing on specific objects' recording, although lacking 3D recording of affected real property units, e.g. Archaeological Cadastre in Greece.

Rights that can be registered in 3D: This includes all the possible information with their needed drawing, notes or clarifications on rights, restrictions and responsibilities (RRRs) for each land parcel/s. Within this field, each country employs different implementations of 3D RRRs' recording due to the lack, in most of the examined countries, of 3D Cadastre legislation. Preceding case studies present similar 3D objects, except of nationally distinct special real property objects, including apartment/horizontal ownership, vertical ownership, servitudes of varying types, rights of superficies, and mining rights. To these, 3D property units and RRRs can be added, applying to Queensland, Victoria and Sweden, while, Latin American countries distinct by recording restrictions based on Aeronautical Code, protected areas and reserved public areas. Regardless the case, cadastral recording of each of the considered as 3D objects in each country, does not involve 3D representation and recording within a full 3D object model. Submission of cross sections partially addresses the issue, given that legislation is based on 2D surface parcels. However, the fact that 3D registration is not provided even in countries where 3D cadastre legislation applies, presents that public and professionals are not familiar with 3D real property concepts in order to exploit real property stratification benefits in full scale.

Table 2: 3D property objects, presentation on cadastral maps and cadastral parcel types per case study

Country	Existing 3D objects (registered or not)	3D cadastral objects (registered)	Presentation of 3D objects to cadastral map	Type of cadastral parcel (2D/3D)
Argentina	-Horizontal property -Easement -Subsoil occupation -Air space occupation -Surface right -Rivers and Lakes -Mines	Horizontal property	2D (orthogonal projection)	2D
Australia (State of Queensland)	- 3D Easements, Leases, Covenants - 3D Roads - Air spaces - 3D Ambulatory boundaries - Water Spaces - Underground space (with or without construction) - Restriction easements (so others cannot obstruct view) - Mining rights - Limitations (above or below a certain height) - Apartments and Common Property - Tunnels, Utilities (network and individual infrastructure) - Carbon abatement zones - Commercial spaces - Car parks - Bridges (pylons and bridge spaces) - Sports spaces (stadium, locker spaces)	- 3D Easements, Leases, Covenants - 3D Roads - Air spaces - 3D Ambulatory boundaries - Water Spaces - Underground space (with or without construction) - Restriction easements (so others cannot obstruct view) - Mining rights - Limitations (above or below a certain height) - Apartments and Common Property - Tunnels, Utilities (network and individual infrastructure) - Carbon abatement zones - Commercial spaces - Car parks - Bridges (pylons and bridge spaces) - Sports spaces (stadium, locker spaces)	- 2D Footprint with 3D Isometric View - Different plan types for 2D, 3D Buildings, and 3D Volumes - Different lot numbering system for 3D - 3D Volumetric plans required to show connection to elevation geodetic control point - Any type of 3D geometry permitted if it can be mathematically defined	3D

Australia (State of Victoria)	-Apartment unit and their accessories, -common property, -depth limitation and airspace	-Apartment unit and their accessories, -common property, -depth limitation and airspace	2D	3D
Austria	-Tunnels -Condominiums -Wine cellars	-Tunnels[1] -Condominiums -Wine cellars	2D	2D
Bulgaria	-Apartments offices -commercial buildings.	Commercial buildings	2D	2D
Canada (Province of Quebec)	-Apartments and commercial buildings, -Underground infrastructure objects as tunnels, subways, -Utility networks -Mining objects	Mandatory: -Apartments and commercial buildings, -Underground infrastructure objects as tunnels, subways -Mining objects Not Mandatory -Utility networks	2D plan with text that refer to complementary PC-plans. PC-plans show vertical profiles and subdivision plans each floor. Altitude, height and volume are indicated on the PC-plans.	2D
China	-Apartment - Commercial buildings - Underground facilities	-Apartment -Commercial buildings	2D	2D
Costa Rica	-Horizontal property -Easement -Subsoil occupation -Air space occupation	Horizontal property	2D (orthogonal projection)	2D
Croatia	-Apartments -Office spaces buildings and other structures -utility lines with associated facilities -traffic infrastructure -water and related objects	-Apartments -Office spaces	2.5D	2D
Czech Republic	-Residential and non-residential premises, -Buildings, -Underground constructions (e.g. tunnels, metro, wine cellars), -Real properties given by the other	-Residential and non-residential premises, -Buildings	2D	2D

	law (e.g. dams, weirs, hydroelectric power station), -Culverts and bridges			
Greece	-Horizontal ownership/ condominium -Vertical ownership -Mines -SRPO -Infrastructures/ utilities	-Horizontal ownership/ condominium -Vertical ownership -Mines -SRPO -Utility servitudes	2D[2]	2D
Jordan	Apartment ownership	Apartments	2D	2D
The Netherlands	-Apartments -offices -commercial buildings, -infrastructure objects -tunnels -bridges	Complex building in Delft	2D (some 3D)	2D
Poland	-Tunnels (railway, subway etc.) -apartments	-Land parcels -Buildings -apartments	2D	2D
Sweden	-Apartments -offices -commercial premises, etc. -infrastructure objects, e.g. tunnels or other large underground facilities, etc.	No limitation on registrable rights	2D[3]	3D (3D property unit)

1 Not shown on the cadastral maps but can be registered as restrictions on the land registry.
2 Special layer for mines and SRPO used.
3 Special symbology of 3D property units.

Existing 3D objects:

Examination of existing 3D objects presents that there is a variety of 3D objects nationally which, apart from specific cases, are of similar nature, e.g. apartment units or underground facilities. However, compared to the list of statutory cadastral objects, only a small number of them is required to be registered to national cadastres. From the presented case studies, it is shown that there are ongoing trends for solving representing and registering 3D cadastral objects both above and underground. For the aboveground objects, it seems that there are no problems in most of the buildings, even they are complex, as long as 3D information is available (3D models, height information, descriptive 3D data, etc.). However, in all countries, the real problem in defining, establishing, registering and managing stratified real property appears in big cities for the underground integration of different activities related to different constructions such as tunnels (cars, rains, subways, etc.), parking, infrastructure, utilities, mines, etc.

Installation of utilities is, in most cases, achieved through the establishment of utility servitudes. Although there is no provision for registration of utility networks in national cadastres, utility servitudes' encumbered land parcels can be traced on cadastral maps and databases. Even in this case, only the 2D projection where servitudes apply along with the servitudes' type are recorded, while information such as height or depth of above or underground networks, along with restrictions or responsibilities deriving from each servitude's type, are not available.

Presentation of 3D objects to cadastral map: It can be derived from the examined case studies that 2D presentation is provided for 3D objects either through projections on surface parcels, as in the majority of the examined countries, or through annotations for the existence of 3D objects on surface parcels (e.g. Quebec, Queensland and specific cases of Greek SRPO). National specifications can be traced, involving 2.5D representations such as use of tags, descriptive height data, e.g. floor number, use of specific symbology or separate thematic layers. Registration of subdivision plans and vertical profiles as provided in the province of Quebec in Canada, or 3D isometric views in the cadastral plans in Queensland, constitutes a different approach presenting 3D characteristics of 3D objects that could facilitate reconstruction of 3D object volumes. However, it needs to be noted that even in countries where 3D Cadastre systems apply and 3D RRRs can be established, there is no provision for 3D objects modelling, that presents both the influence of "surface parcel" concept in land administration, as well as the technical deficiencies in establishing full 3D cadastral systems.

Type of cadastral parcel: Case studies show that only Sweden, Queensland, Victoria, and, to some extent, the Netherlands for condominium rights, have 3D parcels, while the others still have only 2D parcels available. Although 3D cadastral objects may exist, there is still no legally delimited 3D real property parcel available in those countries lacking 3D parcels, although the possibility should be useful in many respects. Only apartment ownership rights are possible in some of the countries. Here it is of importance to consider the difference between 3D objects and 3D parcels, where the 3D parcels can be considered as the legal volumes formed with real rights. 3D property has been introduced as a tool in e.g. Sweden to efficiently manage complex situations of ownership and other rights, restrictions and responsibilities associated with land and could be a possibility also in other countries to legally secure existing 3D objects.

4. CONCLUSIONS

This chapter presents and examines legal status of 3D objects and cadastre of fifteen countries, states and provinces around the world. It examines both Civil and Common Law jurisdictions, also covering different types of cadastral systems. The case studies examined vary as far as the level of 3D Cadastre legislation implementation is concerned, including countries with already operating 3D Cadastre legislation [e.g. Sweden, Australia (Queensland, Victoria)] and others where introduction of 3D Cadastre legislation is under discussion (e.g. Croatia and Poland) either at an advanced level or at an early stage. These, in combination with the different level of cadastral infrastructure among examined countries and national priorities on land administration, constitute a significantly differentiated background, inhibiting comparative process.

Each country applies different terminology to describe 3D objects, although examination of different 3D objects' nature presents that national approaches share similar characteristics. Summarising the concepts of the exemplified case studies in this study, it seems that implemented solutions are not significantly different, although different aspects of 3D property are taken into account, deriving from variations regarding cadastral systems' structure, types of recorded objects and other issues related to national peculiarities of each country's legislation. Apartment ownership concept constitutes the basic 3D object registered in all of the examined countries, although based on 2D registration. Although various other types of 3D objects can be traced in each country, similar or specific nationally-based, the lack of statutory 3D real property legislation results in case specific real property stratification and registration. On the other hand, Swedish, Queensland's and Victorian 3D property units allow for direct real property stratification, thus addressing complexities that the lack of statutory 3D cadastral framework in the rest of the examined countries fails to accommodate.
As it can be concluded from examined case studies where 3D cadastre legislation has been established, introduction of a 3D cadastral system initially requires re-defining real property in 3D space using unambiguous 3D terminology as well as the establishment of legal instruments to subdivide, consolidate and manage 3D real property in 3D space. Examined case studies of Sweden and Australia (Queensland, Victoria), present that such regulations facilitate real property management and clarify, to a significant extent, complex RRRs imposed on land. However, considering the extent of 3D RRRs regulatory framework, it needs to be enhanced by introduction of 3D Public Law Regulations (PLR), amendment of cadastral survey procedures and data recording to incorporate 3D characteristics of real property, as well as transition of current 2D real property to 3D.

5. FURTHER RESEARCH

The research in this chapter shows that researchers from many countries have been investigating the need for 3D documentation of RRRs in their countries. However, only a limited number of them have established an operational 3D cadastre. From the studies the importance of legal aspects of 3D cadastre is evident and we believe that research towards this direction should be continued and promoted. Not only researchers should continue this important task, but also legal professionals should be motivated to participate in 3D cadastre research, using an interdisciplinary approach. The study presented that among the examined countries only Sweden and Victoria provide the possibility to register 3D parcels. This opens several questions:

- To what extent do the authorities realise the need for 3D and how can it be facilitated?
- What are the necessary extensions to existing legislation to be set if advancing an existing cadastre from 2D to 3D?
- What are the departments or expert fields that should be involved in each country to facilitate a 3D cadastre system?
- To what extent is it possible to create a theoretical framework for a 3D cadastre that is independent of the national legislation?
- What are the needed changes in the legislation systems for the transformation from 2D to 3D?

- How can a terminological framework/ontology for 3D cadastre be based on the international standard for land administration, LADM, ISO 19152?
- How can the 3D cadastre and building information modelling (BIM) brought together into a mutual benefit?
- How should such a framework be structured and how could it be translated into geometrical concepts?
- How should economic questions such as cost-benefit-analysis and valuation issues be handled?
- How to raise awareness of 3D issues among other professions, e.g. spatial planners and economists?

These questions will require different kinds of research activities. Given that this study focused on authors' national experience, a more extended research including African and Asian countries, would be of great benefit to 3D cadastre research and the establishment of national 3D Cadastres. It will also be necessary to investigate problems with current implementations and separate technical issues from legal limitations, e.g., is it technically impossible to define a specifically shaped 3D parcel or is this kind of shape not allowed in the legal framework? Therefore, research on empirical guidelines or frameworks for each country, i.e. guiding a process towards the implementation of 3D cadastre systems, might be seen needed for better communications and consensus decisions among the involved stakeholders with their responsibilities. Considering the different levels of the studied countries on the 3D cadastre process, an important outcome from this study might be targeted as a starting point for comprehensive ontology that can potentially be used in integrating land administration information resources. This ontology might be further developed as an evaluation standard for measuring the development and progress level for 3D cadastre in each country.

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Chapter 2. Initial Registration of 3D Parcels

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Key words: 3D Cadastre, Initial Registration, Data Source

SUMMARY

Registering the rights of a 3D parcel should provide certainty of ownership, protection of rights and unambiguous spatial location. While not all cadastral jurisdictions in the world maintain a digital cadastral database, the concepts of such registration hold true regardless of whether it is a paper-based cadastre or a digital one. Similarly, the motivations and purpose for the creation of a 2D cadastre for individual jurisdictions applies to 3D cadastre as well. It provides security of ownership for 3D parcels, protects the rights of the owners, and provides valuable financial instruments such as mortgage, collateral, valuation and taxation. The current life cycle of the development of a land parcel includes processes start from outside the cadastral registration sphere, such as zoning plans and permits, but has a direct impact on how a certain development application is processed. Thus, in considering the changes required to allow a jurisdiction to register 3D, it is important to note the sphere of influence that could have an impact on 3D registration. These include planners, notaries, surveyors, data managers and registrars; however for the purpose of this paper, the research is focused on the core 3D aspects that are institutional, legal and technical. This paper explores approaches and solutions towards the implementation of initial 3D cadastral registration, as derived by current procedures of registration of 3D parcels in various countries worldwide. To this end, the paper analyses the categorisations and approaches of 3D spatial units and examines the validation requirements (constraints) on a cadastral database, at various levels of maturity. In this view, 3D data storage and visualization issues are examined in relation to the level of complexity of various jurisdictions, as provided by the results of the country inventory combined with a worldwide survey in 2010 and updated in 2014 (Van Oosterom, et al., 2014). It appears that significant progress has been achieved in providing legal provisions for the registration of 3D cadastres in many countries and several have started to show 3D information on cadastral plans such as isometric views, vertical profiles or text environment to facilitate such data capture and registration. Moreover, as jurisdictions progress towards an implementation of 3D cadastre, much 3D data collected in other areas (BIM, IFC CityGML files, IndoorGML, InfraGML and LandXML) open up the possibility of creating 3D cadastral database and combining with the existing datasets. The usability, compatibility and portability of these datasets is a low cost solution to one of the costliest phases of the implementation of 3D cadastres, which is the initial 3D data capture.

1. INTRODUCTION

1.1 Background

3D geoinformation is becoming increasingly important towards decision-making, land management and land development. Research has demonstrated the actual added value of 3D information over 2D in the cases of an overall more efficient integration of urban vs. regional planning and management, especially when dealing with 3D underground/aboveground infrastructures. Despite the fact that there has been consistent research within geoinformation science (GISc) on the concept of 3D for more than a decade now, several potentially involved parties are still reluctant to invest in 3D data, 3D techniques and applications. As a consequence, large administration processes relating to urban/ rural planning often run up financial losses simply because generic geoinformation is not part of the process (Stoter, 2011; Stoter et al, 2012).

Regardless of country, an up-to-date property cadastral system is fundamental for sustainable development and environmental protection (Navratil and Frank, 2013; Stoter, 2011; Dale and McLaughlin, 1999). Current worldwide property cadastral registries mainly use 2D parcels to register ownership rights, limited rights and public law restrictions on land. In most cases this is sufficient to give clear information about the legal status of real estate. But in cases of multiple use of space, with stratified property rights in land, the traditional 2D cadastre is not able (or only in a limited way) to reflect geospatial information about those rights in the third dimension. The growing density of land use in urban context is an increasing situation of vertical demarcation of property units. In practical terms, issues stated above do not refer to the need for simple 3D drawing or 3D visualisation capabilities of a stratified reality. The issue dwells in the linkage between two models: a conceptual one and a physical one. The real difficulty is the materialisation of the legal object (a 3D conceptual body) by linking it to its corresponding physical object (in a 2D or a 3D geometric/topologic structure).

1.2 The need for 3D parcel registration

Most modern cadastres register ownership and location details in the land register and therefore 3D registration is intrinsic to many of them. The concept of 2D parcels considered as a 3D column of rights has been around for a long time now. There are however specific extrinsic capabilities of a cadastral system that need to be fully or partially fulfilled so that it can be considered a 3D cadastral system.

The primary capacity of a 3D cadastral system is to be able to register space as a separate entity within the cadastral system. It is not an implicit 3D column of rights but rather an explicit registration of 3D spatial object. The 3D spatial object itself can be a physical 3D structure, an envelope of the physical 3D structure, a slice of rights above or below the surface that in turn may or may not be contiguous to any land or other 3D spatial parcels. In all cases, the main objectives to be achieved in implementing a 3D cadastral model comprise the adoption of (Khoo, 2012):

- an official and authoritative source of 3D cadastral survey information;
- open source format for data exchange and dissemination; and adopting
- International standards in data modelling.

The design of a smart data model that supports 3D parcels (the spatial unit against which one or more homogeneous and unique rights, responsibility or restrictions are associated to the whole entity, as included in a Land Administration system ISO/TC21 19152, 2012), the

automation of cadastral survey data processing and official approval, as well as the integration of the temporal dimension either as separate attributes or via truly integrated 4D spatio-temporal geometry/ topology, may also be prerequisites in this process.
As these cadastral systems progress towards a maturity model of 3D implementation, the complexity of allowed geometric features and the capacity of the system to accommodate these complexities grow too. It thus becomes the responsibility of the cadastral jurisdiction to provide the institutional and legislative framework to facilitate the registration of 3D parcels and to provide the tools for land professionals and other experts, to record, display and visualize 3D cadastral data within the provided framework.
In a 2D cadastre, the basic registration involves person, parcel and rights. Similarly, in a 3D cadastre, the simplest implementation should be able to register these, however, complexities arise when the 3D parcels are geometrically complex and the 3D rights are not clearly defined by legislation. In Shenzhen, pure 3D space (parking and commercial shop) are planned, granted and registered along with their easement to pass to the ground. In Queensland, Australia, any shape of the parcel geometry has been allowed on paper plans as long as it can be defined mathematically, while the registration of these parcels are treated as equivalent to 2D and ownership records are thus stored within the same titling system.
Registering the rights of a 3D parcel provides certainty of ownership, protection of rights and unambiguous spatial location. While not all cadastral jurisdictions in the world maintain a digital cadastral database, the concepts of such registration hold true regardless of whether it is a paper-based cadastre or a digital one. Similarly, the motivations and purpose for the creation of a 2D cadastre for individual jurisdictions hold true for 3D cadastre as well. It provides security of ownership of 3D parcels, protects the rights of the owners, and provides valuable financial instruments such as mortgage, collateral and valuation, also supporting taxation imposed by tax authorities, to the owners of these properties. The jurisdictions need to consider a further investment towards the modification of their cadastral systems to accommodate the current market push towards 3D cadastre.
The current life cycle of the development of a parcel of land includes processes beginning from outside the cadastral registration sphere, such as zoning plans and permits, but has a direct impact on how a specific development application is processed. Thus, in considering the changes required to allow a jurisdiction to register 3D, it is important to note the sphere of influence that could have an impact on 3D registration. These include planners, surveyors, data managers and the registrars, however for the purpose of this paper; the discussions are focused on the core 3D aspects that are institutional, legal and technical issues. Thus, questions that need answering are among others:

- What makes a 3D cadastre? What and why do we register?
- What are the current procedures and what can be modified to adopt 3D?
- Whose responsibility is it? Who can assist with the registration?
- What are the technical challenges in data acquisition, validation, submission, processing, discovery, dissemination and utilisation?
- What are the benefits? What are the current trends?

Finally, although 3D cadastre has been attracting researchers throughout the world for nearly a decade now to identify means for better registration and spatially representation, 3D cadastral technology is only emerging now. Some pilot studies have been accomplished so far and several authors have demonstrated that 3D representations of airspace and subterranean parcels are indeed currently required for 2D + half, representations are unable to handle 3D measurements or 3D spatial queries (including, El-Mekawy et al, 2014; Karabin, 2014; Abdul- Rahman et al, 2012; Khoo, 2012; Soon, 2012; Stoter et al, 2012; Wang et al, 2012; Ying et al, 2012; Zhao et al, 2012; Abdul-Rahman et al, 2011; van Oosterom et al, 2011; Hassan et al, 2010; Chong, 2006; Stoter and van Oosterom, 2006; Valstad, 2005; Stoter, 2004; Stoter et al, 2004).

2. CURRENT STATUS OF 3D REGISTRATION

2.1 Inventory of the current procedures and workflows of registration of 3D parcels in various countries

In this section, a short report of the current procedures and workflows of registration of 3D parcels in various countries is provided. The country selection (presented in alphabetical order), is mainly based on the authors' affiliation, and includes European cases (Croatia, Greece, Portugal, Sweden and The Netherlands), China and the Trinidad and Tobago Caribbean islands. The type of cadastral registration system, the current status of cadastral registration and the efforts towards the establishment of a 3D cadastre are investigated. In a further stage, collaboration with relative group on legal aspects in terms of legal definition of 3D objects seems to be of great scientific interest.

2.1.1 China

The establishment of 3D Cadastre needs legal support. China has its own property system with specific situations. According to Chinese law, all land is owned by the country, and managed by the government. Any party or citizen, except the government, only have the usufruct or use right of the land through public auction, land transaction or land assignment. Land and space management is strongly relevant to land and houses, and generally, there are at least two ministries or departments, in charge of land and housing. However, in Shenzhen, China, there is only one municipality for the land, house, urban planning, surveying and map, geology and sea. That means, almost all space resources are managed by one department, which provides the potential to implement planning and management. Shenzhen, a rapidly developing city during the last 30 years, is facing huge challenges of 3D space development and use. The first pure underground 3D space was sold in 2005 and was granted with certificates, separating the land from its surface. It was the first case in China. That 3D space is a special commercial street named Fengshengding under the main Shennan Boulevard in Shenzhen city. There is a need for a marketplace for intensifying retails in this area where no land on the ground is available to build a bazaar. Instead, this overall bazaar is designed under the main avenue for two layers and its total built area is about 24km^2. Each layer can accommodate a number of small stores along its pavement within such the construction. Figure 1 below shows the use of land space under the ground, and from then, to satisfy these requirements, Shenzhen municipality put forward a 3D cadastral management to support full processes for 3D land/space management.

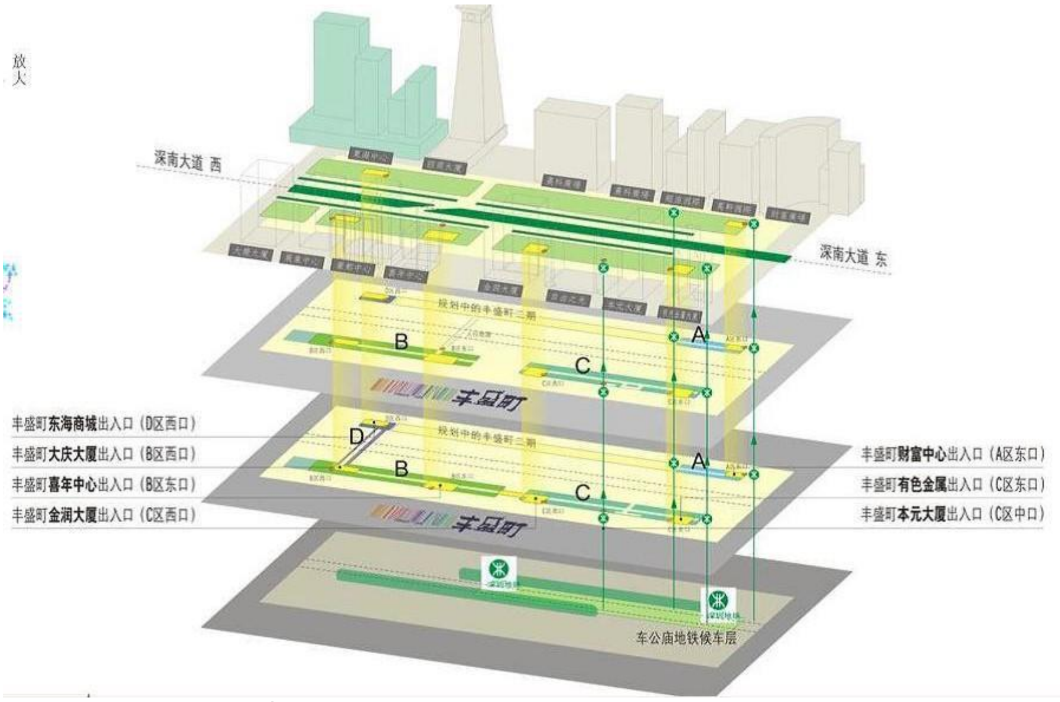


Figure 1. 3D land use of pure 3D underground space

The Interim Regulation on Real Estate Registration was enforced in 2007 and the 136th article points out that the land use right of construction may be created separately on the surface or above or under the ground, thus providing the legal foundation for 3D Cadastre.
In 2007, there is another case on a real 3D parcel with multiple jurisdiction in the Shenzhen Bay Port (Guo, Ying et al, 2011), which is regulated by Shenzhen government and by Hong Kong government. The party of Hong Kong is involved to register the new legal status of a 3D part in the area at the Shenzhen side (Figure 2). Although Shenzhen and Hong Kong are all unified in P.R. China, they enforce different legal systems, which results in the particularity of this area. This special case illustrates that multiple land administration jurisdictions can be imposed on the same 3D cadastral objects as corresponding rights, responsibilities and restrictions taken by corresponding parties.

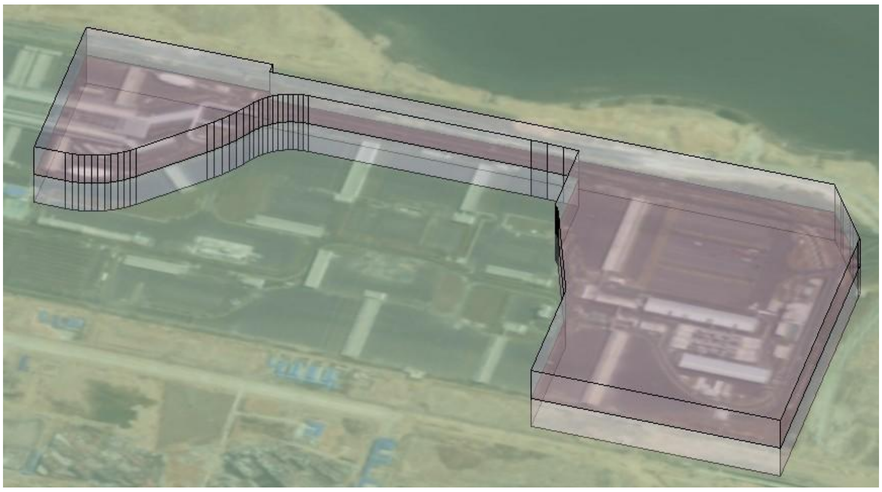


Figure 2. 3D space with multiple jurisdictions in Shenzhen Bay Port area

In order to satisfy the rapid need of 3D space in Shenzhen, in 2012, Shenzhen Municipal People's Congress revised the law "Shenzhen special economic zone real estate registration ordinance", to support the auction, transaction, grant and certification of 3D space. During the Third International Workshop of 3D Cadastre, the online automatic office system of Urban Planning, Land and Resources Commission of Shenzhen Municipality was demonstrated to illustrate the workflow of 3D land space planning and management. From the first pure 3D space granted in 2005, Shenzhen Municipal Government has handled more than 8 hundreds cases in 3D land planning, granting and registering, totally with more than 1500 km^2 with vertical projective areas (Guo and Luo et al., 2014). These 3D space applications and practices include the subway, underground garage or shop center, arcade, etc. A new zone named 'Qianhai', from the start of zero, the empty sea region, has been enforced to plan, construct, manage and use in fully 3D from the beginning, and this will completely promote the application of 3D planning and 3D Cadastre.

2.1.2 Croatia

Land Administration System in Croatia consists of two fundamental registers (Cadastre and Land Book). The description of the land/property as information for property sheet A of the Land Book is registered in the Cadastre. For registered property, rights and charges are recorded in sheets B and C. The Cadastre was created for the entire Croatian territory in the 19th century as a part of the Austro-Hungarian Francis survey. Until 1880 the documentation, cadastral plan and lists of holders for all cadastral municipalities have been produced. Cadastre was created for the purpose of fair taxation of land. It was maintained in accordance with the regulations and was changing according to political changes since its establishment. The main purpose, the calculation of land tax was retained until 1995, when such land taxation was abolished. At that point the cadastre lost its tax purposes, and became increasingly used for legal purposes.

After the establishment of the Cadastre in the late 19th century, judicial authorities have established Land Book based on the description of the land (information on the cadastral parcels). Land description (number and other attributes of cadastral parcels) was marked in the sheet A, for each cadastral parcel the owner was registered in the sheet B, and charges in the sheet C. Unfortunately, changes in social and political arrangements violated the consistency of these two registers. Today, the registered data does not correspond to the real situation for considerable number of land parcels. Bringing these two register up to date is the greatest challenge for Land Administration System in Croatia.

Changes in the Land Tenure system, which radically changed in 1990's when Croatia declared independence and left the socialist political system, have significantly contributed to inconsistencies. Under the socialist system two types of ownership existed, private and social. The latter one was preferred. Various political actions (nationalization etc.) tried to make as much land/property become social. After independence only one form of ownership was introduced. Social ownership was abolished by regulations, and private owners were determined depending on the situation. The principle "superficies solo cedit" was reintroduced. That significantly influenced registrations in Land Administration System. In accordance with that principle, everything connected with land (buildings, trees, etc.), above or below the Earth's surface, is one property, respecting a functional approach rather than "vertical" (Roić, 2012).

Since 2010 all cadastral and Land Book data are in electronic form, but they are in different models and databases maintained by various software. The establishment of the Joint

Information System which provides integrated management of Cadastre and Land Book is in progress. The system has been established, and data migration should be completed by the end of 2015. This should enable coordinated functioning of those two registers and uniform handling which was not the case in the past. Cadastre Joint Information System (JIS) is designed as a central repository of data. Access for data maintenance and viewing is provided by a web client. Officers, depending on the role can modify data, and external users have view access only.

Property description in the registers is based on a two-dimensional representation from the cadastral map which does not allow the registration of interests in strata. Implicitly, the legal unity of the property indicates the legal objects that belongs to individual (co)owner. Registration of separate parts of property (apartment, office space) was regulated in 1997. Production of documentation with a spatial representation (2.5D) of separate parts of the whole property is prescribed for buildings. The documentation determines the co-ownership share of each owner in the entire property with the presentation of common parts (Figure 3). Plans of the parts of property are in the local system (building) without absolute Z coordinates. It is also used for the allocation of costs for management and maintenance of the property. Documentation for registration, and registration are regularly made for new buildings and are rare for those built before 1997 (Vučić at al., 2013).

In addition to the Real Property Cadastre in Croatia, there is also the Utility Cadastre, a register of technical features of utility lines bearing no legal significance. Legal relations regarding utilities are registered in Land Book, in practice very rarely, as an easement right on land where these infrastructure are placed.

Apart from the possibility of registration of private rights in the strata, the registration of legal regimes (maritime good, protected areas, by spatial planning defined land use etc.) is foreseen in the Real Property Cadastre since 1999. That and the registration of public utility infrastructure should give users a more complete description of the interests that exist on a particular land. For now, the registration of public rights is in its beginning. Legislation and data model of Joint Information System don’t yet foresee spatial representation in 3D, and it is not possible to store the 3D geometry of 3D legal objects. Also Utility Cadastre is not in electronic form and not part of JIS. Therefore, it still cannot be combined with the Real Property Cadastre.

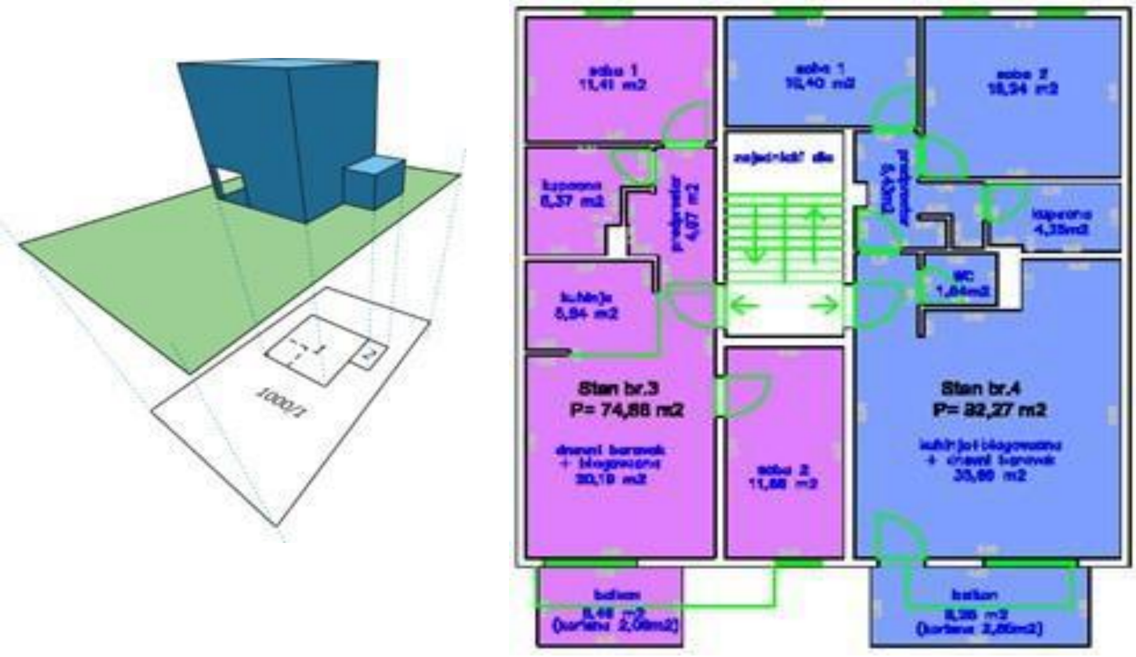


Figure 3. Property on the cadastral map and presentation of parts (separate and common) per floor

2.1.3 <u>Greece</u>

The ongoing Hellenic Cadastre (HC) Project aims at replacing the existing Registration and Mortgage Offices are assisted by an integrated information system that records legal, technical and other data about real estate properties, along with the rights and restrictions on them. These property data and registrable rights are collected during the “cadastral survey” procedure; each person or legal entity that has rights to specific land parcel in the area under surveying, is invited to submit declaration for its real properties while depicting them on cadastral diagrams. The declaration form also includes the geographical description of the properties (shape, location and size) and information about deeds that establish or change rights on real estate properties. Current administrative source documents are deed based, although after completion of the HC project, title based registration will be implemented.

The current digital cadastral database (DCDB) includes all information collected during the cadastral survey and is organized into descriptive and spatial part, comprising administrative divisions, land-parcels, buildings (only the building footprint is presented on the cadastral maps), mines, sites of exclusive use, easements, true-orthophotos, DSM, topographic drawings, as well as beneficiaries, registered rights, titles etc. The DCDB does not contain representation of 3D parcels, although a separate layer will be used to incorporate objects with 3D aspects.

In Greece, almost all 3D parcels (3D spatial units in LADM terminology) are constrained to be within one surface 2D parcel, with limited exceptions described in the Greek Civil Code (CC). They usually relate to physical objects with some exceptions providing for encroachments or the right of superficies and of course the Special Real Property Objects (SRPOs), underground parking lots and potential floors. Disconnected parts of a single 3D parcel are only allowed in case of condominium. Regarding spatial limitation of 3D parcels, Greek C.C. stipulates that ownership extends above and below the surface, however the landowner cannot object unless he has practical interest in opposing to it. Limitations on the range of rights related to 3D spatial units exist only in case of lands where ancient antiquities are discovered, as well as mines and rights of superficies. Legislation for 3D descriptions of parcels includes Horizontal Property Law 3741/1929, Civil Code Articles 1001, 1002, 1010 and Law 3986/2011. For natural resources (groundwater, mining rights), the Law regulating cadastral operation stipulates recording of mining rights but not as 3D parcels, while infrastructure and utility networks' registration as an entity is not operational.

Apartment units in condominium schemes are the most important types of registered 3D building units, in accordance to the Horizontal Property Law, and their 3D boundaries are the middle of floors, walls and ceilings. Common property inside the building is commonly owned by the apartment owners and is not directly registered in the Cadastre. Each apartment gets a unique cadastral number specified in terms of building lot code, parcel number, building code, and floor and apartment code. Apartments are described in deeds and the building's footprint as drawing, submitted in paper format or electronically. Dimensions are shown on survey plans. There are no provisions for isometric views, nor are they stored in the DCDB.

For the geometrical representation of 3D spatial units, plans of survey guarantee x/y coordinates in relation to the Greek national reference system (HGRS87), while older plans in older or arbitrary systems may also exist. Height representation is referenced to the Greek national system, although z coordinates are not stored in the DCDB. The earth surface (height) is not stored in the DCDB, although there are DTMs and DEMs available in the National Cadastre and Mapping Agency (NCMA) and the Hellenic Military Geography Service (HMGS). The sources of elevation for the 2D surface parcel are trigonometric points of principle reference network even though in most cases, elevation source is arbitrarily defined. Survey plans do not carry 3D parcel representation, though in recent plans, point heights are included. The legislation describing the requirements for plans of survey in 3D only includes regulations for height recording but there is no provision for 3D. SRPO are registered as .dwg files at a different layer. 3D property entities (condominium, mines, SRPO) are registered in the 2D DCDB. Specific symbols are used to depict presence of 3D cadastral objects (in case of SRPO) on the 2D cadastral map.

According to the competent authority, NCMA, so far the HC is operational for 20% of real estate rights through 103 Registry Offices while cadastral surveying is in progress for another 20% and tendering procedures are running for the rest 40% of them (Rokos, 2014), based on IT infrastructure and digital orthophotomaps' national coverage. Therefore, the HC has still a lot to do to reach its goals and adequately address issues that relate to 3D registration and representation of cadastral data.

2.1.4 Portugal

As far as Portugal is concerned, a prototype of a centralised distributed cadastral management system, implementing a 2D approach, has been conceived: the "Sistema Nacional de Exploração e Gestão da Informação Cadastral" called SiNErGIC (PCM 2006). This in turn will be the basis of the national cadastral information system (SNIC). Its technical implementation is however far from being concluded due to a major issue: geospatial data capture in the field has revealed to be an endless task for it is laborious and expensive. The first official step towards the establishment of a national registry of land parcels in Portugal was taken back in 1801. Clearly stating how authorities were aware in those days of the great value of a measured coordinate-based cadastre, cosmographers (One who studies, describes, depicts, and measures the Earth and/or the visible universe, including geography and astronomy) were the practitioners of those days appointed by royal decree to be in charge of the organisation of both “a cadastre and a general registry book of real estates within the kingdom”. For several reasons, such registry was never launched though until 1836, when the national real estate registry (the “Registo Predial”, see Figure 1) actually started being implemented (Silva et al, 2005). However, it was not until 1926 that coordinated cadastre surveys were actually carried out. Given Portugal’s territorial issue, with a few million small real estates scattered across a rather irregular topography, fieldwork has revealed to be a rather complex and demanding operation and has not covered the whole country yet. Coordinated cadastre surveys are currently being accomplished district-by-district covering both rural and urban real estates (Figure 4). By the end of 2014 more than 50% of the mainland’s territory had been surveyed, though this only corresponds to roughly 1/3 of the total number of properties in the country.

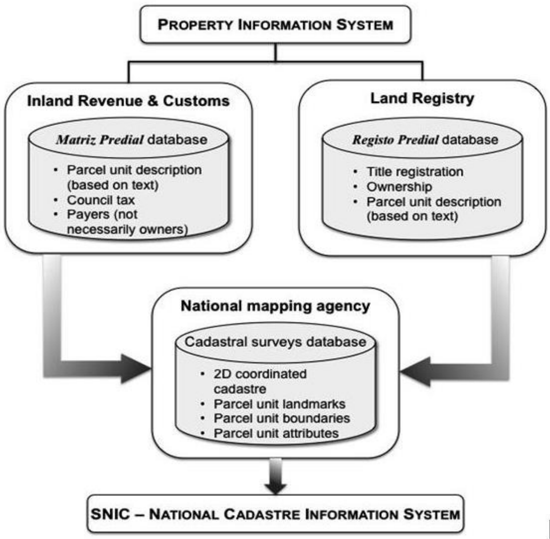


Figure 4. Overview of the current property information system in Portugal

2.1.5 Sweden

Effective and secure real property registration is a cornerstone in Swedish land management. Cadastral information is registered in the Swedish Real Property Register, which contains information of more than 3.3 million real properties and joint property units.

Real property formation and alteration procedures are executed by the cadastral authorities; Lantmäteriet, the Swedish mapping, cadastral and land registration authority, and a limited number of municipalities within their jurisdictions. All changes are updated in the real property register on a daily basis after obtaining legal force. The real property register is managed by Lantmäteriet. The register is used by a large number of registered users, such as financial institutions and about 900 000 queries to the system are done each month. The register is even accessible to the general public through various internet services (El-Mekawi et al. 2014).

The register consists of a textual part (i.e. land register) and a geographical part (i.e. the cadastral index map). The textual part holds information on the title holder, easements and other rights, restrictions and responsibilities, mortgages, unique areal property identification numbers, etc. The cadastral index map contain the spatial extension of property units, joint property easements and other rights, restrictions and responsibilities, unique areal property identification numbers, some planning information, etc. The land register and index map contains information on both 2D and 3D real property units, including 3D property space, i.e. horizontally and vertically delimited space belonging to a property unit other than a 3D property (Paulsson, 2012) (see Figure 5).

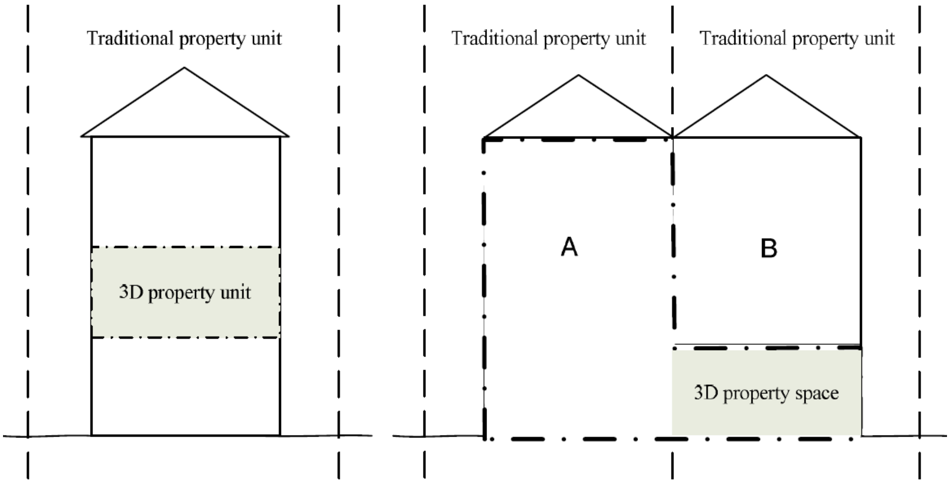


Figure 5. 3D property unit and 3D property space (Paulsson, 2012)

A building can through 3D property formation be divided into different (legal) purposes, for example commercial purposes on the ground floor and dwelling purposes on the upper floors and garage(s) below ground. 3D property formation is also used for other constructions such as tunnels to secure rights of ownership and/or use. A unique reference number is referring to the legal cadastral formation document case file, which contain all legal documents, including construction drawings with details on the physical extension of boundaries, e.g. that a boundary follows the outside of a specific wall. The documents are often scanned construction blue-prints, being used as background for legal documentation.

A 3D property is in principle treated as a traditional 2D property, but additional 3D information is registered on 3D properties in the land register and cadastral index map. The land register specifies whether it is a 3D property or 3D property space, x and y coordinates and gives a brief description of the location in height, e.g. between level "CA" +31.2 meters and level "CA" +55 meters on the construction drawing, which is part of the legal documents, as shown in the example in Figure 6.

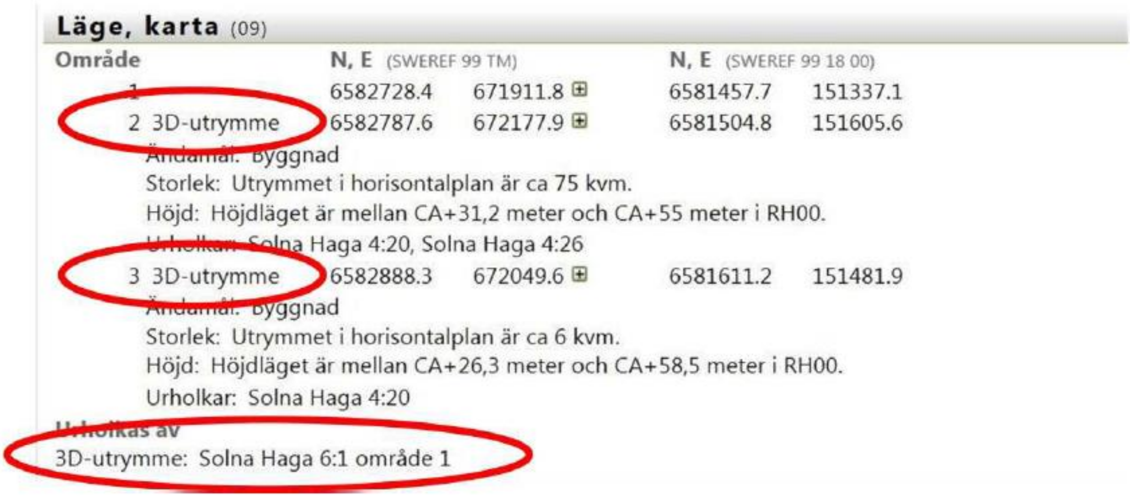


Figure 6. Example of textual 3D information (in Swedish) in the land register (El-Mekawy et al., 2014)

The 2D footprint of the 3D property is shown in the digital index map by marking the boundaries with dotted lines. The footprint is covered with a surface texture and a property id., e.g. "\Sörby 1:5\", is added as cartographic text in the cadastral index map. "\xx\ indicate it is a 3D property. See

Figure 7. In this figure the real property "Sörby 1:4" is a 2D property being caved out by the 3D property space "Sörby 1:5 area 2". "Sörby 1:5" is a traditional (i.e. 2D) property where area 2 is carving out "Sörby 1:5". "Sörby 1:14" is a 3D property carving out "Sörby 1:5" (Lantmäteriet, 2004; El-Mekawy et al. 2014).

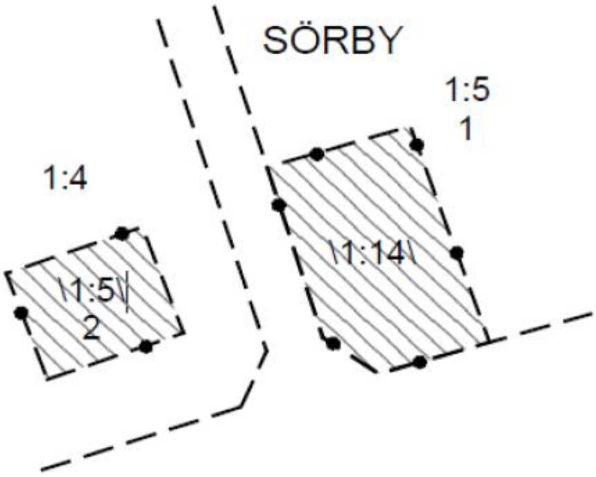


Figure 7. Cartographic representation of 3D property in the cadastral index map

2.1.6 The Netherlands

The design and implementation of the cadastral system extension for registration of 3D rights and restrictions in the Netherlands (Stoter et al 2013) fits within the ISO 19152, Land Administration Domain Model (LADM) international standard. The implementation is conducted in two phases. The first phase of the solution did not require a change of the legal and cadastral frameworks, it is a short term solution for most urgent cases, and it is also used to gain experience in the challenging domain of 3D cadastre. In the first half of 2016 the first actual 3D Parcels were registered at the Netherlands Cadastre (after many years of research)[1]. This procedure improves the registration and it includes an extension of the cadastral system to accept 3D descriptions in 3D pdf format as part of the deed. This solution improves the 'old practice', where the multi-level property situations are projected on the plane and with the potential consequence is that the ground parcel(s) will be subdivided based on those projections. The resulting fragmentation in the registration was in several cases quite unclear because many small parcels may be necessary to register one single object (Stoter et al 2013). The first phase of 3D cadastral implementation exploits one of the LADM conceptual modelling options, more specifically associating LA_SpatialUnit with a 3D drawing (LA_SpatialSource, playing the role of a sketch). The solution fits within current cadastral and legal frameworks and could therefore be implemented within a short time frame. In fact the major breakthrough is that the option to register a digital 3D drawing (possibly legally binding) will actually be practiced (by training/ involving stakeholders, notary, project developers, municipalities, etc.). In addition, because the 3D drawing provides insight into the spatial

[1] The pdf can be obtained from: https://www.kadaster.nl/web/artikel/download/NieuwDownloadpagina-24.htm and https://www.kadaster.nl/web/Nieuws/Nieuwsberichten/Bericht/Wereldprimeur-inschrijving-met-rechten-in-3D-1.htm

dimensions of the right, new 2D parcels do not need to be created to delineate the exact boundaries of the 3D property on the ground parcel and creation of fragmented parcels can be avoided. The information required in the 3D representation to understand the multi-level property situation are identified as follows: 2D ground parcels that overlap (and footprint of 3D legal Volumes), 3D (graphical) description of legal space, 2D cross sections with accompanying annotations (for apartments), objects needed for reference and orientation in the 3D environment (3D topography/ buildings, same as for the 2D Cadastre), and localise the 3D legal volume in both a local coordinate system and the national height datum system. The first registration (Stoter et al, 2016) concerns the ‘Spoorzone Delft’ project (see Figure 8) and includes six legal volumes described in the 3D pdf in land register (see Figure 9):

1. current building of land owner (municipal office)
2. railway tunnel
3. passenger area (including cycle parking and stairs to platform)
4. station hall (on ground level)
5. stairs & elevators
6. technical installations

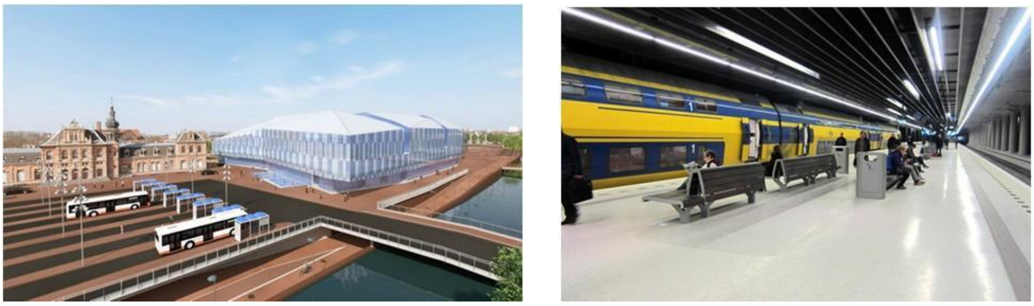


Figure 8. Impression of the ‘Spoorzone Delft’ project

The various owners (holders of rights involved) are Delft municipality, NS Vastgoed, and Railinfratrust.

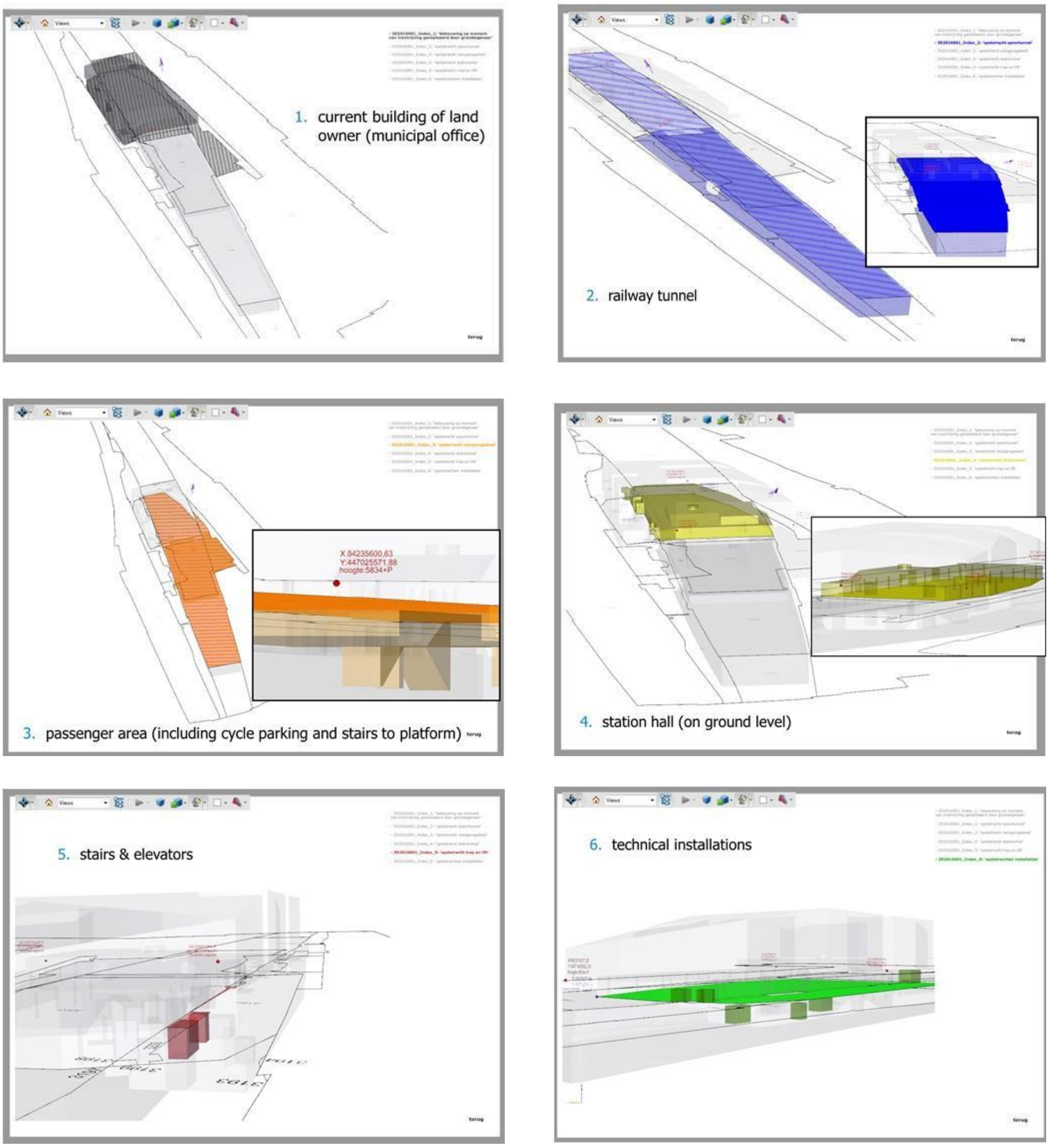


Figure 9. The six legal volumes described in the 3D pdf in land register

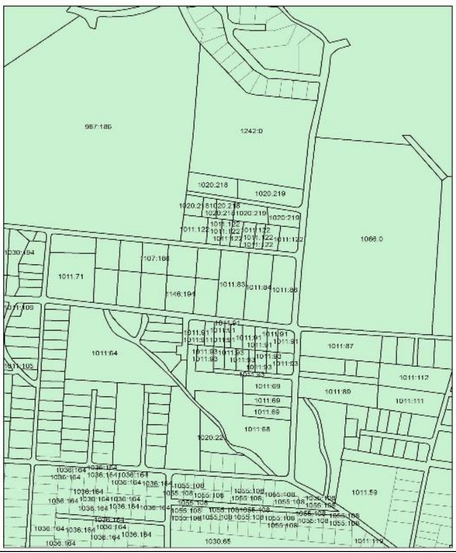
One of the drawbacks of this solution is that it is not possible to validate the 3D cadastral representations (Are the volumes closed? Are the neighbors' non-overlapping?). The second phase is research in progress and comprises the actual inclusion of the 3D data in the registration, enabling complete validation and even better 3D data management and dissemination. Based on experiences to be collected from the first phase and experiences from other countries, the solution for the second phase will be further refined and subsequently implemented in due time.

2.1.7 Trinidad and Tobago

A cadastre provides a description of the extent and nature of rights, restrictions, and responsibilities held in land, broadly defined to include earth, water, and artificial structures positioned in or on either earth or water. Where verbal descriptions are inadequate to precisely and unambiguously define or redefine the land that is the subject of a transaction of sale, mortgage, or transfer, graphic descriptions become necessary. In some instances 2D graphic descriptions are adequate but when these do not suffice, 3D and 4D graphic descriptions become important. The economic or social benefit of having a 3D or 4D cadastre must outweigh the costs of establishing the system. This is particularly so for developing countries such as Trinidad and Tobago.

The Cadastre in Trinidad and Tobago is currently incomplete and out of date. Digital data exists of 200,000 parcels as shown in Figure 10, but thousands of plans have been scanned but not yet added to the Cadastre. Cadastral survey plans continue to be submitted in hardcopy and this further restricts the speed of updating of the cadastre. The cadastre is a digital index of uncoordinated surveys that provides information on the location of the field survey plans. However, because of the cadastre’s lack of currency, searches for information can become frustrating or, at worst, futile. There is no unique parcel identifier that can assist with this search and addresses are non-standardized although a new initiative is attempting to rectify this latter issue with a proposed zip coding. Parcels are defined and redefined relative to the surrounding parcels and their boundaries, which are marked at the turns by boundary irons. Coordinates, therefore, have no legal standing.

There are no immediate plans to transition the existing 2D cadastre to a 3D cadastre as there is much rationalization of the existing data to perform first. In the meantime, strata (condominium) rights are indicated in vertical sections in insets on the 2D cadastral plans (see Figure 11), and subsurface reserves and mining rights are shown on 2D plans related to the surface parcels. The location of these 3D properties are not visualized on the 2D cadastre, but the physical buildings can be seen on the underlying topographic imagery, which is current to 2015 as shown in Figure 12a. No elevations are recorded on these plans to a standard datum but heights relative to the ground can be included in the vertical sections.



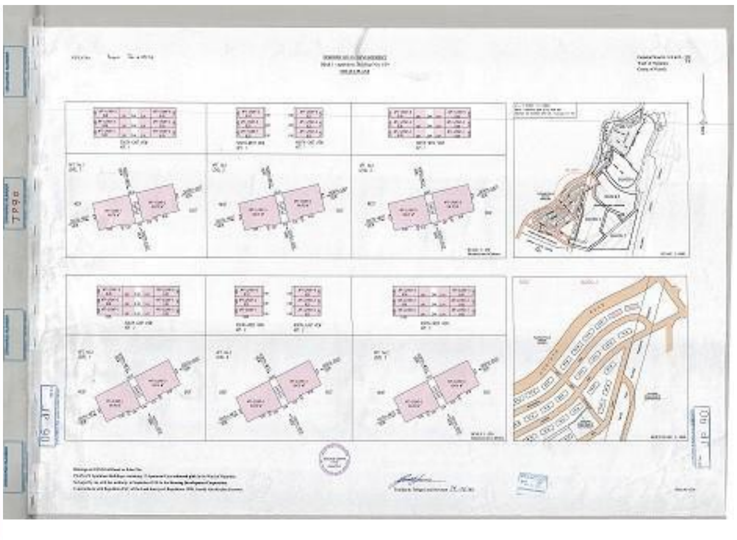


Fig. 10. Trinidad and Tobago’s digital 2D cadastre Fig.11 Vertical sections on survey plans depict 3D rights

The individual parcels in the graphical cadastre are also not linked to the registered deeds and titles containing information on interests that are located at the legal registry of the Registrar General’s Office. Rights, restrictions and responsibilities are therefore not graphically displayed in the cadastre but some may be expressed textually in the deed document at the registry. Urban and regional development plans are held at a separate state institution, they are approximate in definition of extent, and are not linked to the cadastre. There is no fiscal cadastre as the valuation rolls are manual and contain no graphics. The majority of registered interests are deeds based with a small minority being supported by title registration. The cadastre does not show the level of interest but solely the extent of the interest. While all title documents refer to or contain a graphical description of the parcel in a survey plan, many deeds that date back several decades do not contain a survey plan but a verbal description of the parcel referring to adjoiners which no longer exist. A recent project upgraded the Cadastral Management Information System (CMIS) which includes the procedure for receiving new cadastral plans, checking and approving them, and entering them on the database. As part of this project, new software was installed that speeds up the maintenance of the cadastre, however the limited human resource is still an issue that can restrict this progress.

The description of the rights themselves is done textually in the deed document, the rights to the individual condominium being expressed as a share in a company possessing the entire property. 3D registration therefore occurs when the deed is prepared that reflects that a transaction of a percentage of shares, representing a parcel shown in a graphical cadastral plan attached, has occurred. This demonstrates that 3D cadastres can be manual and represented in 2D space similar to how 3D digital cadastres are reflected in 2D space but visualized in 3D. The legislation in Trinidad and Tobago gives the authority to the land surveying profession and the Director of Surveys to make rules for the graphic description of any rights held in land (Griffith-Charles and Edwards, 2014).

Trinidad and Tobago is therefore at a more rudimentary level of physical 3D registration, graphically recording only those 3D physical spaces that are in condominiums with the use of 2D plans with vertical sections describing the third dimension. While Griffith-Charles and Sutherland (2013) analyze the costs and benefits of instituting a 3D cadastre in Trinidad and Tobago, and suggest only partial and primarily urban implementation, the current weakened economy discourages a full scale launch into its establishment. Full coverage LiDAR data taken over the country in 2015 as shown in Figure 12b, which can support the development of a visualization of the physical cadastral boundaries where they intersect with the conceptual cadastral boundaries.

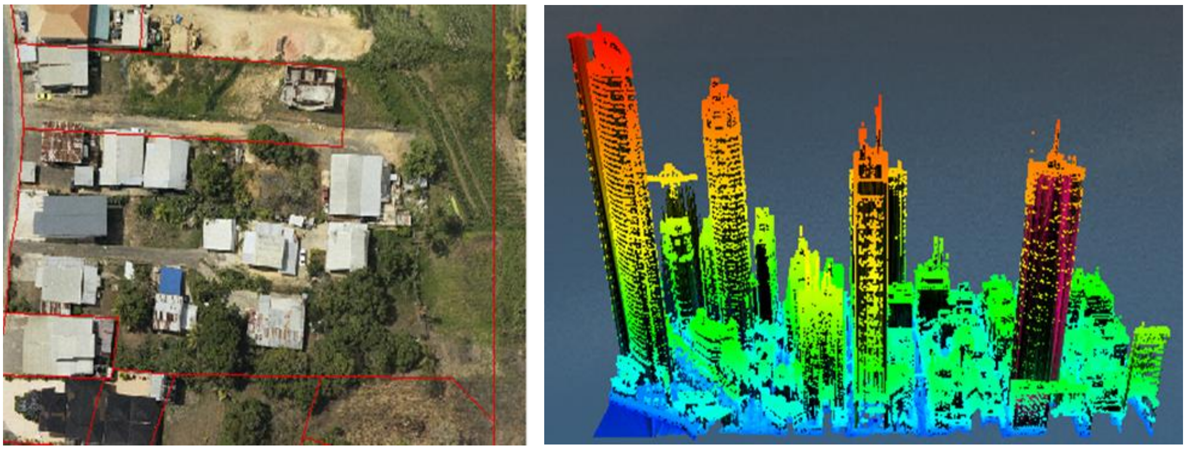


Figure 12 (a) Orthophotography indicates topography related to the cadaster (b) LiDAR data of urban Trinidad and Tobago

2.2 Comparison between the presented countries

In this session, a comparison between the presented countries is provided (see Table 1), summarizing common characteristics and differences that relate to cadastral registration issues. The definition and proper use of the concepts of 3D parcels, 3D spatial units, 3D space or 3D objects, are essential and need to be clarified, in order to efficiently compare the various cadastral registration approaches and draw conclusions on best initial registration practices. It appears that the countries examined have certain legal provisions for the registration of 3D parcels, or vertical/ cross sections of 3D information and/ or textual description in their cadastral database. Concerning the interaction between legislation and registration, it seems that many cadastral legislations were created/ updated in the seventies or eighties, with added 3D parts in later years, and may contain strong links to the then existing technical solutions. This may hinder an effective data collection and storage using today's technology. The result may therefore not only be technical issues to accommodate legal statutes, but also the change of legislation to accommodate technical solutions possible today.

Table 1: Summarizing common characteristics and differences

COUNTRY	REGISTRATION SYSTEM	LEGAL PROVISION FOR 3D PARCEL REGISTRATION	BASIC UNIT FOR 3D OBJECTS	EXISTING CADASTRAL DATA SOURCES
CHINA	Titles registration system Not unified system	Yes	3D real property unit	- Land Register and cadastral map (for several cities in digital format) - 3D pilot Cadastres
CROATIA	Title - based registration system	Yes	- Cadastral parcel - 2D models with tags 2.5D - 2D plans with 3D textual information	- Real property Cadastre and thematic utility cadastre - Land Book
GREECE	Currently, under transition from Deeds Register to Title - based registration system	Only for SPROs	- 2D cadastral parcel - 3D SPRO at different layers	-Ongoing National Cadastre project -Deeds Registration System
PORTUGAL	Deeds Register	No	Parcel unit	National Cadastral Information System
SWEDEN	Titles registration system	Yes	- 2D representation of 3D objects	- Swedish mapping, cadastral & land registration - Limited number of Municipalities
THE NETHERLANDS	Deeds registration system	Yes	-3D description in pdf -spatial unit with 3D (digital) drawing	Cadastre, Land Registry and Mapping Agency
TRINIDAD AND TOBAGO	Deeds and Titles registration system	Yes	Surface lot with vertical sections	Registrar General Office

2.3 Analysis of categorisations and approaches to 3D spatial units

More details on the classes of 3D spatial units can be found in (Thompson et al, 2015). The following is a summary. The first major division of spatial units is between:

2D Spatial Unit: The spatial unit is completely defined by the 2D location of points (x/y or latitude/longitude) along its boundary. This type of spatial unit is in effect a prism of space unbounded above and below. If a point (x, y, z) is within the spatial unit, then (x, y, z’) is also within the spatial unit. There may be restrictions on the allowable value of z’, but there is no explicitly defined “top” or “bottom” of the spatial unit (Figure 12a).

Building Format Unit: This spatial unit is legally defined by the structure of the building that contains the unit. It may be defined to the outside of walls, or to the middle of walls etc. There may or may not be a diagram of the unit, but any measurements on the plan are not normative (Figure 12b).

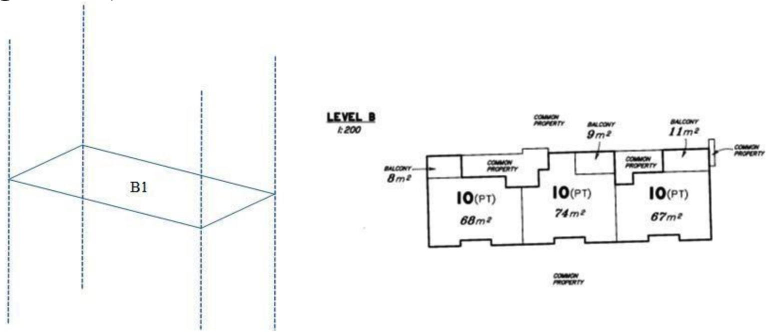


Figure 12. (a) (Left) 2D spatial unit, (b) (Right)/spatial units defined by the structure (the buildings walls)

3D Spatial Unit: This spatial unit is defined by a set of bounding faces, which are themselves defined by a set of 3D points and an interpretation. For example, a set of planar faces, cylindrical faces etc. There are many variations, including whether the boundaries are defined by natural features or fiat (Smith, 1994) lines, how they are fixed, what datum is used etc. Within the set of 3D Spatial Units, there are several categories:

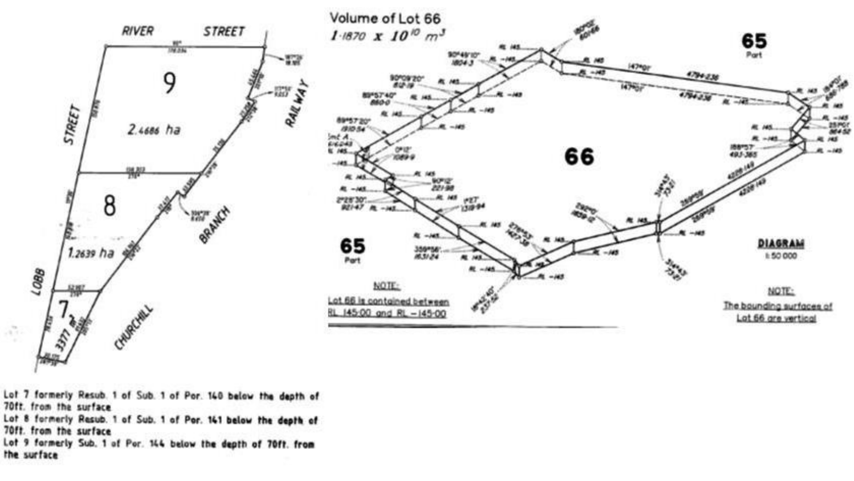


Figure 13. (a) (Left) Below the depth of spatial units, (b) (Right) A (very large) simple slice

Above/Below Depth or Height: These are commonly used in mining areas, but could also be used to limit building heights - for example near airports/ transmission towers etc. These are simply 2D Spatial Units with a height restriction (Figure 13a, above).

Polygonal Slice: This is the most common form of 3D spatial unit. It is in effect a 2D spatial unit, with a defined top and bottom. It can also be considered to be an extruded polygon (Figure 13b, above). As with the 2D Spatial Units, these can be defined in terms of natural features. For example, a Spatial Unit could be defined as extending to 100m below ground level.

Single-Valued Stepped Slice: (Figure 14a). This is also a fairly common 3D Spatial Unit. It can be viewed as the union of a number of Polygonal Slices so that for every point (x,y,z) in the interior of the Spatial Unit, there is exists zmax, zmin such that zmin < z < zmax Þ (x,y,z) is interior to the spatial unit. These spatial units can be quite complex.

Multi-Valued Stepped Slice: (Figure 14b). This is a Spatial Unit whose boundary faces are all either horizontal or vertical.

General 3D Spatial Units: (Figure 15). This is the “catch-all” of spatial units, which fail to fit in one of the above categories. These can be difficult to store or visualise, but tend to be relatively few in number.

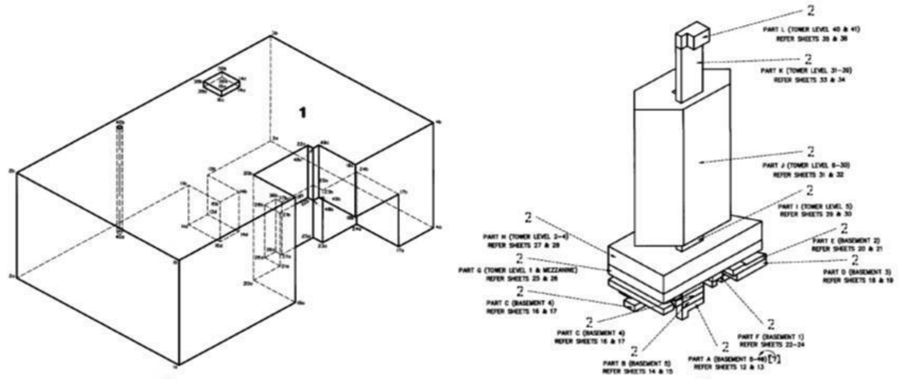


Figure 14. (a) (Left) a single-valued stepped slice, (b) (Right) a multi-valued stepped slice

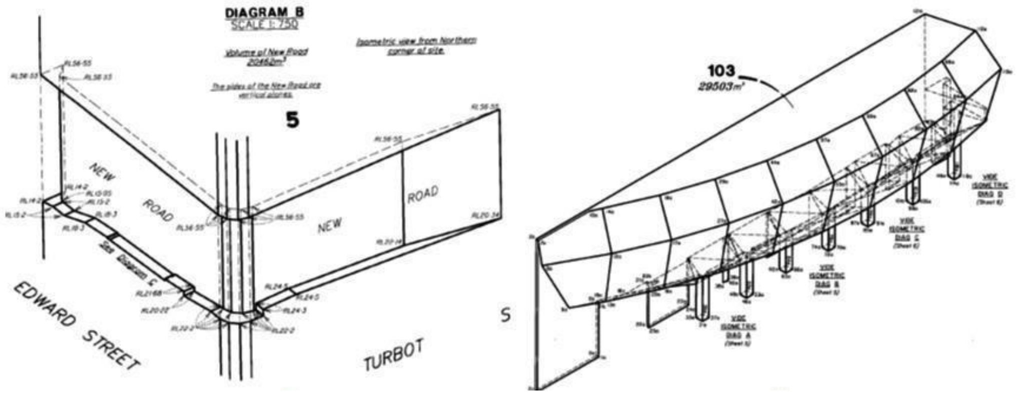


Figure 15. Some general 3D spatial units

There is also the very important *Balance Spatial Unit*. This can be of any complexity as above, but represents the remainder of a 2D spatial unit when all the 3D spatial units defined within it have been excised (Figure 16).

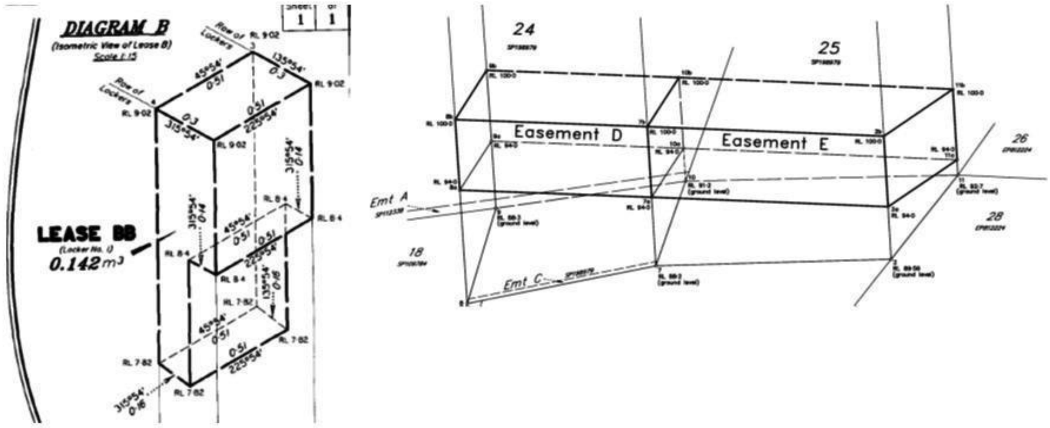


Figure 16. (a) (Left) a small lot excised from a much larger 2D spatial unit (a golf course), (b) (Right) 3D easement within 2D parcel (but this is not excised)

Constraints (validation requirements) on a cadastral database can be at various levels of maturity:

Non-overlapping 2D spatial units: In all cases, there seems to be an underlying requirement that a 2D "base cadastre" should be identifiable. This should allow the range of the jurisdiction to be defined by a set of non-overlapping 2D spatial units.

Complete non-overlapping 2D: In many cases this coverage is also required to be complete (i.e. every point in the jurisdiction must belong to one and only one base 2D spatial unit).

Non-base 2D spatial units: Frequently, there is a requirement to define a non-base spatial unit that represents a secondary interest in part or all of a base spatial unit. (e.g. the right to traverse land). Thus a non-base spatial unit may overlap one or more base spatial units, and one or more other non-base spatial units.

3D spatial units represented as footprints: The next level of sophistication is to carry all 3D spatial units in the cadastral database as "footprints". Here a 2D "flattened" representation of the spatial unit is stored as if it were a secondary interest over the base (2D) spatial unit.

Simple 3D as extruded polygons: There is very little extra complexity to attribute the "footprints" of 3D spatial units with a minimum and/or maximum elevation. This will allow a correct representation of simple 3D spatial units (such as slices), or an approximation of any 3D spatial unit. Even such an approximation may be sufficient to ensure separation between parcels.

Non-overlapping 3D coverage: One important aspect of a 3D cadastral database is to ensure that overlap of 3D spatial units is prevented (as is the case with the 2D coverage).

Complete non-overlapping in 3D: By considering the 2D spatial units to be infinite height prisms of space, it is possible to ensure a complete, non-overlapping 3D coverage of space.

Non-base (secondary interest) 3D: Because, even in 3D there is the possibility of secondary interests on part or all of a 3D spatial unit, there is the need to allow non-base (may need a new term) to overlap one or more base parcels in 3D.

3. LEGAL AND TECHNICAL ISSUES

3.1 Sources of 3D data

To minimize the financial and human resources required to establish 3D cadastres, particularly in developing countries, low cost and existing sources of data may be leveraged. This may mean that intermediate stages of development will be necessary before a complete and precise 3D cadastre is achieved. As with the systematic adjudication and titling that is necessary to convert from deed systems to title systems, a systematic instead of sporadic process is required if the 2D system is to be converted to 3D. A mandatory process is also necessary and preferred over a voluntary process. Legislation will therefore be required to mandate upgrading from stage to stage. While manual survey processes may be cheaper where modern equipment is expensive, laser scanning of internal and external 3D details can speed up the data acquisition and make it more efficient.

3.2 Legal issues

The legal framework for establishing 3D Cadastre can be divided into one that refers to the establishment of property and other that stipulates registration of property in the official cadastral registers. Property rights relations among persons regarding the properties are usually regulated by the real property rights legislation (e.g. The Civil Code) and the registration of properties by the cadastral legislation. According to general property rights legislation, legal objects and their boundaries, may follow physical objects, but they are not necessarily coincident (Figure 17). As such Land Administration Domain Model (LADM) focuses on legal space rather than on physical space, though in some specific instances, both may well happen to have the same extent. Registration of legal objects and related rights in the official registers and level of detail required, usually prescribe cadastral legislation. Variations may exist amongst Common law jurisdictions and Civil Law jurisdictions to some extent (Kitsakis and Dimopoulou, 2014; Ho et al., 2013).

3.2.1 Legal objects

Definitions of legal objects usually start from the Earth's surface, which is divided into parcels of rights holders. Furthermore, whatever is attached to land is part of it, whereby the attachment considers the functional principle. This approach has once meant: who owns the Earth's surface is the owner of all from the center of the Earth to infinity (hell/ heaven) (Figure 17).

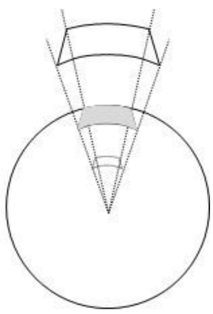


Figure 17. Legal object

However, today by many regulations of public law, which are or will be adopted at the national or the local level, in this space are drilled holes. For example, if the owner finds mineral

resources beneath the earth's surface and begins to use them, very soon he will be warned by the competent public authorities that his right below the earth's surface is very shallow. If an archaeological site lies beneath the land, the owner will have the opportunity to become familiar with numerous special regulations that define these conditions and restrict his right of ownership. Generally, digging caves on the land may be irregular, if it is of sufficient depth, if special permission has not been obtained.
Similar situation exists in the opposite direction when building on a block of land. The air belongs to all, while to the land owner only what is built. Using vacant space is subject to conditions of spatial planning documents as public law regulations. So the owner of the parcel is left with only a thin layer of the earth's surface and what is built on it. Rights to mineral resources depend on the terms of specific legislation, and are usually controlled by public law regulations. For the exploitation of mineral resources it is often necessary to obtain a permit. Rights are always established in "3D" intrinsically, although for cadastral registration 2D plans are usually required. For the harmonization of this complexity of physical/ legal objects and the public laws that are set up, improvements on the spatial dimension of property registration are required.

3.2.2 Registration of legal objects

Legal objects, as defined by the legislation, are materialized by physical objects where legal object is generally identical to the physical object. If this is to a certain extent not the case, then it is indirectly determined by physical objects (e.g. safety zone is x meters from ...) and can be modeled /visualized in 3D. Cadastral legislation prescribes measurement, modelling and visualization of legal objects on the cadastral map. Part of a land (parcel), can be easily registered in the cadastre as a legal object, most commonly as boundary polygons and is usually shown on the plane cadastral map. However, for the registration of increasingly complex physical objects, which are usually divided into more legal objects and influenced by numerous public rights, cadastral legislation is not prepared. Predefined parcel space cannot be easily modeled and visualized on 2D cadastral map.
Physical objects that have footprint under/ over more parcels, are functionally attached to only one parcel and are part of that legal object. Footprint registration/ visualization may create confusion for users and misinterpretation of the legal relationships. In some jurisdictions it solves the registration of legal objects in layers by 2.5D representations that are separate from the cadastral map. Such an approach may help temporarily, but is not a solution because it is difficult to get a complete information about property right relationships. Visualization on 2D cadastral map can only be an indication of the complexity of the relationship on the land.
Although regulations on Cadastre change slowly, for the successful registration of legal objects in 3D it is necessary to improve the cadastral legislation. 3D cadastre is only advanced modelling and presentation of existing real world relationships regarding rights on properties.

3.3 Technical Issues

3.3.1 Data submission and validation

Through the data acquisition techniques, 3D data can be created in different environment to model the 3D shapes. In the process of constructing 3D models, users need to submit or upload the data source to data center to create 3D model, in order to build spatial topology of 3D models and spatial analysis (e.g. spatial conflict detection). Data formats can be SketchUp file, AutoCAD file, 3D Max file and coordinate file in excel format, even CityGML file (Ying et al., 2014). According to different 3D spatial application and spatial complexity, users can select the appropriate data source to deliver 3D shapes. For example, for a complex building, users can divide it into several parts and describe them each with a coordinate file, and after submission, there will be special process to rebuild the holistic 3D model through the geometric locations and topological relationships.

To ensure correct spatial analysis, many judgment rules and validations on 3D data and 3D models are necessary. 1) Basic data examinations. These tests include the eligibility of coordinates. Are they in correct range with suitable precision? Are there many points with same coordinate? Replicated point or same point? 2) Possibility to construct a 3D model. Is it possible to construct a 3D model or several models with input 3D data? These are many rules to test this possibility/impossibility, including face-connecting, Euler formula (Ying et al., 2015; Thompson and van Oosterom, 2012). It should be worth mentioning that 3D model here is not limited to simple solid defined in ISO19107 and LADM, includes the 3D non-manifold model (Ying et al., 2015). 3) Spatial location and conflict test in 3D scene. The input or submitted data may have spatial relationships and conflicts with other existing data in a database, either 2D data or 3D data surrounding them. If there are spatial occupation conflicts, the input data should check their geometrics and locations. If there are small gaps between them, this situation is acceptable to ensure these is no spatial conflicts among the close 3D models, which is a vital factor in urban 3D planning and construction. On the other hand, sometime, these gaps should be handled to merge into neighbor/adjacent 3D models in order to keep consistent geometric data and topological relationships for efficient data management. Spatial relationships between the input data/models and existing models, including 2D overlay and connection, 3D topological connections, should be correctly recognized after the submission.

3.3.2 Data storage, processing, dissemination and visualization in 3D

The approach to storing and visualization of 3D spatial units depends on the level of complexity that exists within the jurisdiction. For example, if the highest level of complexity is the Polygonal Slice (or the Above/ Below level of) the level of functionality required for storage can be a simple 2D database that allows for overlapping non-base polygons and can carry the height limit attributes.

Where the full complexity of 3D Spatial Units is needed, a more sophisticated database, and even more importantly, more sophisticated visualization tools will be needed.

3D as external database objects: It has been suggested that the 3D spatial units be kept separate from the 2D spatial units (because the issues in storage are so different). So that a GIS type solution is used to store and retrieve the 2D spatial unit coverage, while a CAD system is used to hold the 3D spatial units. This is not an optimal solution because the 3D spatial units must be represented in the GIS (as flattened "footprints") to avoid holes being left in the coverage. Thus we are left with two representations of the same spatial unit in different databases, having to be independently updated. From time to time, it is necessary to adjust the corner positions of a cadastral database - to account for improvements in accuracy of measurement, changes of datum, or even movement of the land itself. It is vital in these operations that the 3D spatial units do not become detached from their position in the 2D coverage.

Some cadastral databases have persistent identifiers for cadastral corners, and these can be used to ensure that the 2D and 3D spatial units that share corner locations can be kept in registration. Considering all these issues, the ideal form of storage of 3D parcels in a corporate database is that 2D parcels and 2D versions of the 3D parcels be kept in a single table (thus visible to 2D GIS), with the extra information required to represent the 3D parcels in full in a

linked table or location.
Specifically:

3D spatial units represented as footprints: If the decision is made only to store “footprints” a simple 2D spatial database is sufficient.

Simple 3D as extruded polygons: If the decision is to approximate all 3D parcels with simple polygonal slices (or if the jurisdiction has no spatial units more complex) a 2D spatial database, with attributes of top and bottom elevation is sufficient. This is also true for databases with above/below height/depth spatial units.

More complex 3D spatial units: Here, it is still probably justified to extract and store the “footprint” of all 3D parcels, so that a complete 2D view of the database using classical GIS is available. In addition to this, it is preferable that the 3D version of the spatial units are closely associated with the 2D version. When adjustments are made to the 2D spatial unit fabric, the association between the 2D and 3D representations must be preserved.

Dissemination and Visualization: As has been discussed above, a 2D view of all parcels is essential, and this should be available to a classical GIS. In addition, a 3D “view” of the cadastre is needed, showing all 2D as well as 3D spatial units in a common form similar to a 3D city model. In this view, it is essential that sub-surface spatial units are accessible and viewable.

4. CONCLUSIONS AND FUTURE TRENDS

From worldwide surveys (van Oosterom, et al., 2011 and 2014), it was found that no country has a fully implemented functional 3D cadastre. The same applies from the outcomes of the selected countries presented. There are examples of partial implementation, but the functionalities are always limited in some way. Significant progress has been achieved in providing legal provisions for the registration of 3D cadastre in several countries and many have started to show some kind of 3D information on cadastral plans, such as isometric views, vertical profiles or textual information, to facilitate data capture and registration.
In all cases, the whole cycle of the cadastral plan starts from survey data capture, progresses to data processing for plan creation, then data storage with registering authority, then data visualization and dissemination. Although research has progressed in all aspects of the cadastral plan life cycle, the current study mainly focused on data creation and initial registration aspects. As jurisdictions have progressed towards a partial implementation of 3D cadastre, much 3D data has been collected in other areas such as Building Information Models (BIM), which have opened up the possibility of creating a 3D database from existing dataset. The focus of such research is the usability, compatibility and portability of these datasets, which might be a low cost solution to one of the costliest phases of the implementation of 3D cadastre which is the data capture. In this respect, the questions raised at the beginning of this research (session 1.2) can be summarized (in the same order) as follows:

- The primary capacity for a 3D cadastre is to be able to register space as a separate entity within the cadastral system. What we register, is not an implicit 3D column of rights but rather an explicit registration of 3D spatial objects.
- In order to transition to 3D, the cadastral jurisdiction must provide institutional and legislative framework to facilitate the registration of 3D parcels and the tools for land professionals to record and display 3D cadastral data within the provided framework.
- Responsibilities may consider a sphere of influence with an impact on 3D registration,

including planners, surveyors, data managers and the registrars.
- Technical challenges include: modern 3D data acquisition techniques, appropriate level of complexity within jurisdictions, validation requirements at various levels of maturity and,
- Benefits provided encompass, certainty of ownership, protection of rights of 3D parcels, unambiguous spatial location and valuable financial instruments.

Finally, with the integration of 3D technology with low cost solutions, sources of 3D data other than those already in use can be exploited, including other 3D topographical data, LiDAR data, 2D or 3D floorplans which are not from BIMs, Laser surveys of individual building units, and data from Volunteer Geographic Information (VGI). The true cost of such rapid data acquisition though comes when attempting to link to the existing cadastral framework and validating such data. However, for initial implementation, these are invaluable sources of information and when a cadastre reaches a certain level of maturity, it might even serve as a source to these BIM and VGI datasets. Complex solutions may not be required for initial implementation of 3D cadastre when none exists previously, and such cost effective solution will assist to establish a proper 3D cadastre faster.
When such implementation takes shape, the future consideration is on cleaning these datasets to be as close to the accuracy and functionality of the existing 2D cadastre as possible. These may however be done in refresh cycles with progressive levels of maturity or a systematic upgrade process can be undertaken with focus on an area at a time. Attention can then be given to 3D data capture and creating an institutional, legal and technical framework for its successful implementation.

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Chapter 3. 3D Cadastral Information Modelling

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Key words: 3D Information Modelling, 3D Cadastre, Standardization, LADM, CityGML, IndoorGML, LandXML, BIM/IFC

SUMMARY

In this chapter we address various aspects of 3D Cadastral Information Modelling. Of course, this is closely related to the legal framework and initial registration as presented in the first two chapters. Cadastral data models, such as the Land Administration Domain Model, which include 3D support, have been developed for legal information modelling and management purposes without providing correspondence to the object's physical counterparts. Building Information Models and virtual 3D topographic/ city models (e.g. LandXML, InfraGML, CityGML, IndoorGML) can be used to describe the physical reality. The main focus of such models is on the physical and functional characteristics of urban structures (Aien et al, 2015). However, by definition, those two aspects need to be interrelated; i.e. a tunnel, a building, a mine, etc. always have both a legal status and boundaries as well as a physical description; while it is evident that their integration would maximise their utility and flexibility to support different applications. A model driven architecture approach, including the formalization of constraints is preferred. In the model driven architecture design approach as proposed by the Object Management Group the information model, often expressed in the form of a UML class diagram is the core of the development. This so-called Platform Independent Model (PIM, as presented in the current chapter) is then transformed into Platform Specific Model (PSM). This could be a relational database schema for a spatial DBMS (as will be discussed in the next chapter), or XML schema for a data exchange format or the structure of maps, forms and tables as used in the graphic user interface of a spatial application. Constraints have proved effective in providing the solutions needed to avoid errors and enable maintenance of data quality; thus the need to specify and implement them. This chapter explores possibilities of linking 3D legal right, restriction, responsibilities spaces, modelled with the Land Administration Domain Model (ISO 19152), with physical reality of 3D objects (described via CityGML, IFC, InfraGML, etc).

1. INTRODUCTION

When considering the complete development life cycle of rural and, in particular, urban areas, related activities should all support 3D representations and not just the cadastral registration of the 3D spatial units associated with the correct RRRs (rights, restrictions, responsibilities) and parties (van Oosterom, 2011). The exact naming of these activities differs from country to country, and their order of execution may differ. However, in some form or another, the following steps performed by various public and private actors, which are all somehow related to 3D cadastral registration, are recognized:

- Develop and register zoning plans in 3D.
- Register (public law) restrictions in 3D.
- Design new spatial units/objects in 3D.
- Acquire appropriate land/space in 3D.
- Request and provide (after appropriate checks) permits in 3D.
- Obtain and register financing (mortgage) for future objects in 3D.
- Survey and measure spatial units/objects (after construction) in 3D.
- Submit associated rights (RRR)/parties and their spatial units in 3D.
- Validate and check submitted data (and register if accepted) in 3D.
- Store and analyze the spatial units in 3D.
- Disseminate, visualize and use the spatial units in 3D.

Several of the activities and their information flows need to be structurally upgraded from 2D to 3D representations. Because this chain of activities requires good information flows between the various actors, it is crucial that the meaning of this information is well defined—an important role for standardization. Very relevant are ISO 19152 (LADM) and ISO 19156 (Observations and Measurements), and highly related and partially overlapping is the scope of the new OGC's Land Development – Standards Working Group (LD-SWG), with more of a focus on civil engineering information, e.g., InfraGML (aligned with LADM). This phenomenon is especially true for 3D cadastre registration because it is being tested and practiced in an increasing number of countries. For example, for buildings (above/below/on the surface or constructions such as tunnels and bridges), and (utility) networks, this overlap is clear. LADM is focusing on the spatial/legal side, which could be complemented by civil engineering physical (model) extensions. It is important to reuse existing standards as a foundation and to continue from that point to ensure interoperability in the domain in our developing environment!

We start by giving an overview of the modelling requirements, i.e. defining, the scope (in section 2) of the 3D Cadastral Information Model. Next, we present an overview of the relevant standardized information models in Section 3. This could be considered as composed of a range of standards starting with pure cadastre/land administration standards, gradually moving towards standards for topography. The Land Administration Domain Model (LADM, ISO 19152) plays a key role. Similar to the 2D situation, topography is commonly used for reference or orientation purposes to make clear the actual location and size of the parcels. Topography and cadastral information does not have to be maintained by the same organization and/or in the same system, they can be combined when needed via the Spatial Data Infrastructure (SDI). In the case of 3D, the link between cadastral information and topography seems to be even tighter. Very often 3D legal spaces with RRRs attached are created near actual or planned constructions, such as buildings, roads, tunnels, bridges, utilities, etc.

Quite a number of countries are active in developing 3D Cadastral Information Models, based on standards as much as possible, but applied to the needs of the country. A selection of these 3D (LADM) country profiles is given in Section 4: Russia, Malaysia, Greece, Israel and Poland. The last section of this chapter analyses the gap between what is currently available (standards, country profiles) and the current and future requirements.

2. MODELLING REQUIREMENTS

In this section, various types of modelling requirement for 3D Cadastral information are introduced. The core requirement is that various types of 3D parcels should be supported. Additionally, the temporal dimension must be included, allowing representation of multiple versions of the same spatial object, and the link with 3D topography. It is further explained why it is important to have constraints explicitly included in the model and why it is critical to have standard-based modelling.

2.1 Types of 3D parcels

An initial categorization of 3D Parcels was given in Thompson et al. (2015) and forms the starting point for the further investigations into suitable corresponding database representations exchange format, and data capture encodings. The following categories were introduced, now listed in the order of growing complexity:

1. 2D spatial unit (actually prism of 3D space): defined by a 2 dimensional shape.
2. Building format spatial unit: defined by the extents of an existing or planned structure (e.g. apartment).
3. Semi-open spatial unit: defined by 2D shape with upper or lower surface.
4. Polygonal slice spatial unit: defined by 2D shape with upper and lower surface.
5. Single-valued stepped spatial unit: defined by only horizontal and vertical boundaries (among others the facestring from 2D space) and single valued[1].
6. Multi-valued stepped spatial unit: as above but now multi valued.
7. General 3D spatial unit: defined also by boundaries other than horizontal and vertical.

The category of General 3D spatial units can be further refined: 2-manifold boundaries required or not, partly open/completely closed volume, planar/curved boundaries, multi-valued single/multi-volume, etc. (Thompson and van Oosterom 2012).

The problem of mixing 2D land parcel definitions with the range of 3D parcels in a corporate database and exchange format encodings is one of the most basic issues to be solved in creating a modern approach to Cadastral modelling. Various approaches have been suggested in Thompson et al. (2015):

1. Keep the 3D parcels in a separate database from the rest of the 2D database.
2. Simply store footprints only, with no reference to 3D definitions at all.
3. Keep a representation all parcels in the main database in 2D form only (with the 3D parcels represented by “footprints”). The full 3D definition of the 3D spatial units is kept in another form (in CAD or pdf format) and may be obtained from a document archive.

[1] The volume is called single valued if there is no pair of points within the spatial unit with the same (x,y) coordinates which have a point from outside the spatial unit between them.

4. Store all parcels in the same database, with 3D parcels being approximated by a "slice" (a polygon with a horizontal top and bottom surfaces) which contains the parcel (but may be a loose fit).
5. Convert all parcels to 3D form and store in a single database.
6. Integrate 2D parcels and 3D parcels in the same database and make sure they fit well together.

Beyond simple mapping applications, a basic requirement to be satisfied by a corporate database is to answer the query "*given a spatial unit, what are its adjoiners?*" Of the above methods only methods 5 and 6 can satisfy this query directly. The others either cannot respond at all, or will give incorrect answers (Thompson et al., 2016). Thompson (2015) published the finding that levels of encoding can co-exist within the same cadastral database and that 2D and 3D parcels can be mixed.
Digital Terrain Model and Digital Surface Model can be superimposed with spatial units and 'intersections' with existing 2D spatial units can be created. Those intersections can be considered as spatial units by themselves (for example by defining 'the above ground portion of spatial unit …').

2.2 4D time
Next to the spatial (3D) aspect of rights and restrictions, the temporal aspect, the fourth dimension of interests in real estate, is an important aspect of cadastral registration (van Oosterom et al, 2006). Rights, responsibilities and restrictions clearly have a temporal element. A further category of examples of the need for 4D cadastral information is when a record of history is required on a particular property, or when historic information on land use development in a certain region is needed to support future land policy – this is the real-world time aspect. The final category is where a history of the database content is needed – this is the system time aspect (van Oosterom, Maessen, and Quak, 2002).
The principle of an efficient management of object life cycle was elaborated on in Seifert et al. (2016), where the data model requires a unique identifier for each object, together with a designated time stamp for creation and deletion of that object. However, when an object is deleted during an updating process, the object will not be physically removed from the data base. Only the thematic relevance has ended, not the existence of the object as a historic record. A "deleted" object is then considered the as historical information which can be easily distinguished from the actual information. Sometimes there are changes to an object which do not require the deletion of the object (e.g. the name of a person changes). In that case also the different versions of an object can be stored. Since every object carries life cycle information, the storage of historical objects and versions of objects is not limited to any specific object type. This approach supports the temporal dimension independent from the spatial dimensions, by adding separate versioning or time-range attributes.
It is clear that time has always played an important role in cadastral systems, but so far this temporal aspect has been treated quite independently from the spatial (2D or 3D) aspect. The current cadastral systems deal with both 3D situations and temporal 4D aspects on an ad hoc basis within existing cadastral procedures. Because this information is not registered in a uniform way, insight in all relevant aspects (who has which rights at a certain moment, for what space and for what period(s)) is frequently a problem. The basis of a cadastre has not been set up on a 4D space-time partition model. Time is not (yet) integrated in the data types of the topology/geometry. It is currently treated as a separate attribute (tmin/tmax everywhere and

timeSpec in RRR). One could imagine full spatio-temporal Cadastral Object representations for the definition of moving object with RRRs attached; e.g. to define grazing rights moving/changing-location over seasons (2D and time) or a Marine cadastre with moving/changing fishing rights in the ocean (3D and time). A more integrated approach of the temporal and spatial aspects is wanted. Deep integrated treatment of space and time in one internal 4D data type representation has clear benefits for the future realization of a 4D cadastre (van Oosterom et al, 2006):

1. optimal efficient 4D searching (specifying both space and time in same query) can only be realized if a 4D data type (and index/clustering) is used, otherwise the DBMS (query plan) has to select first on space and then on time (or the reverse order). However, note that even 2D index/cluster is most likely sufficient for reasonable performance – as the 3rd dimension and time are less selective. So, this is not a strong argument for adoption of 4D data types;
2. with true 4D data types, parent-child relationships between parcels (the lineage) are neighbour queries in a topological structure (neighbours for which at least the time attribute changes), which is potentially more efficient than a spatio-temporal overlay as needed in the non-integrated approach; see Figure 1 (left): Parcel P3 has parent parcel P1 and children parcels P4 and P5;
3. 4D analysis: 'Overlap' appears in, for example, land consolidation procedures; here an 'old' and 'new' parcellations exist temporally in parallel. Another example is the question: do two moving cattle rights have spatio-temporal overlap/touch (Figure 1 right)? If stored and represented in the database by a 4D data type, this is just a simple query. If stored as separated attributes, this is not a trivial query to answer;
4. but most important, if we do want the full (4D) partition (of 3D space+time, with no overlaps, no gaps) as our foundation for a 4D Cadastre, having true 4D geometry and topology (with space and time integrated) is the most solid foundation.

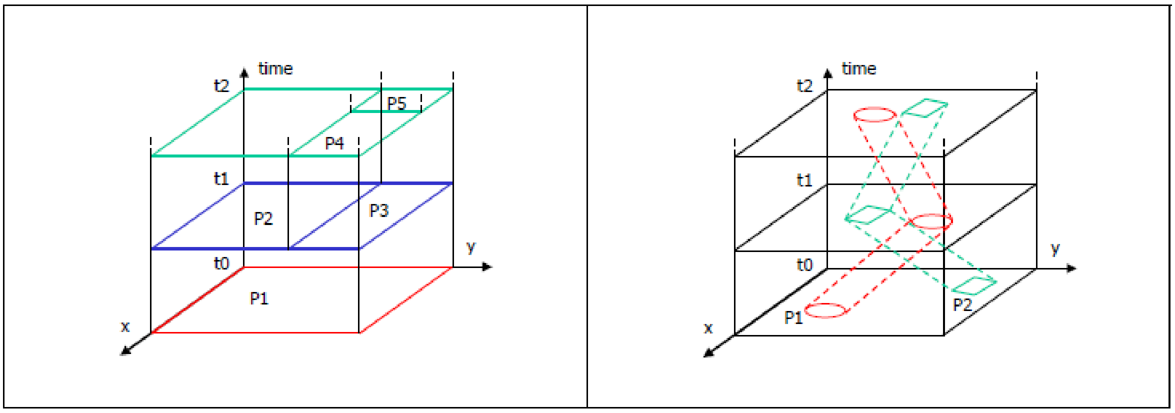

Figure 1. Integrated treatment of space (2D) and time: left the subdivision of parcels and right the representation of moving cattle

2.3 Represent multiple versions of the same point

In land administration and surveying the ‘same point’ is often represented in multiple ways. However, these different representations must be modelled properly and linked. Examples of these cases include: a point as included on a design (BIM/IFC – Building Information Model/Industry Foundation Classes), after/during construction the same point can be surveyed multiple times (with slightly different coordinates); a point converted from a local coordinate

reference system to the national grid; a newly surveyed point fitted in existing cadastral mapping (van Oosterom et al, 2011).
Besides linking the various representation, the class representing the 'point' must include the attributes such as: point identifier; estimated accuracy; interpolation role (this is the role of point in the structure of a straight line or a curve, e.g. end, isolated, mid, mid_arc, or start); monumentation (this is the type of monumentation in the field, e.g. beacon, cornerstone, marker, not_marked); original location (the calculated coordinates from original observations); point type (e.g. geodetic control points, or points with or without source documents); production method; and finally zero or more transformations (and transformed location, so that the transformed location defines a new version of the point). Transformations include for example affine transformations but also mathematical computations such as least square adjustments.

2.4 Spatial Data Infrastructure links to 3D topography and BIM
It is important to remember the relationship between the concepts of 'legal' and 'physical' objects in 2D (Döner et al, 2011). In 2D, a parcel is a legal object indicating the extent of property rights (ownership, leasehold, easement, limited real rights such as emphyteusis in civil law) of which the boundaries are not always visible features of the terrain. Only when overlaying the parcel boundaries maintained in the cadastral database with topography (i.e. representation of physical objects), the real estate objects can be fully visualised. In a full 3D cadastre, a volumetric parcel is also a conceptual (legal) object, not necessarily visible in reality, and only indirectly related to physical objects. Therefore, it can also be used for other purposes than the registration of ownership of 3D physical objects, for example, to register the ownership of a safety zone for a tunnel or to register the ownership of some space to assure future view from a building. In most cases in 2D, parcels are related to physical objects because the ownership of a piece of land implies ownership of all physical objects that are attached to it, if located within the parcel boundaries. In the same way, the ownership of a 3D parcel implies the ownership of all physical objects that are located within the space, for example tunnel or utility network. This explains the need for 3D topographic data in the context of 3D Cadastre. Currently the cities are producing the city models according to the CityGML. Such data could be then potentially reused for 3D cadastre purposes.
For example, Building Information Models (BIM) are used to update the cadastre in Costa Rica (van Oosterom et al., 2014). Behnam et al. (2016) present usage of BIM as a feasible approach for managing land and property information in high-rise administration. They propose an extension to the BIM standard to show the potential capability of using BIM for modeling 3D ownership rights. Note: architectural drawings have long been used to represent apartment complexes in cadastral systems. It is frequently the case that the implementation of the design in reality differs from the design itself. This may require re-surveys after the design is constructed.
For any developments that require spatial data, often the fusion of diverse spatial datasets is unavoidable. For instance, in developing a 3D cadastral database serving various purposes, data may need to be sourced from different spatial datasets such as: building design models in BIM format, topographic and built environment information in CityGML, and cadastral legal boundaries in LandXML (Soon et al., 2014). Note: it is common that there are differences in the geometry in different sources because of different data acquisition methods and different scales. A BIM designed object has a scale 1:1. It may fit to reality but maybe not to the cadastral map. If the cadastral map is locally adjusted there may be overlaps with surrounding parcels. In the context of cadastral requirements, the CityGML does not contain any features describing

the legal information about spatial objects (Góźdź et al., 2014). As also stated in Góźdź et al. (2014), the Land Administration Domain Model also constitutes a generic expandable domain model, designed to be connected in a SDI setting to data from other domain models and other standards (e.g. CityGML, INSPIRE Data Specifications).
The link between LA_SpatialUnit and ExtPhysicalBuildingUnit (as represented according to CityGML,r IndoorGML or BIM/IFC) is an important topic to explore further; e.g. which LoD (Level of Deatil) is being referred to (see Figure 2). Obviously, when a single building contains multiple spatial units, then indoor is needed (LoD4 in CityGML or preferrably IndoorGML or BIM/IFC representations). Note that the link between the LA_SpatialUnit and ExtPhysicalBuildingUnit (or ExtPhysicalUtilityNetwork) does not have direct legal implication. However, if the corresponding 3D spaces are very different, then someone should take action. Actual reusing of (3D) topographic objects as boundaries of legal spaces could be a dangerous step (if physical object should move or change, then also legal spaces might be affected unintentionally), so care is needed (Thompson et al., 2016).

Figure 2. The five LODs of CityGML 2.0. The geometric detail and semantic complexity increase, ending with LOD4 containing indoor features (Biljecki et al., 2016)

Not only the geometrical aspect, but also the semantic aspect of data sources should also be considered. Building data in BIM/IFC, CityGML and LandXML are produced based on different knowledge domains (design, physical and legal). This causes conceptual and terminological differences between data sources if these data sources are to be integrated (Soon et. al. (2014)).
Rönsdorf et al. (2014) demonstrated how the OGC CityGML standard can be used to provide an encoding for 3D land administration information. The basic principles of the integration by mapping key feature classes in both standards are shown. Further they conclude that the same approach will be applicable for country or region specific profiles of ISO 19152 and encourage practical experimentation with this.
The possibilities of applying CityGML for cadastral purposes are elaborated in Góźdź et al. (2014) with particular attention to the 3D representation of buildings. A proposal for the CityGML-LADM Application Domain Extension (ADE) is presented, drawing particular attention to the buildings, both addressing their physical aspects and their legal counterparts. Technical realization of the issue has been executed at the conceptual level by integration the CityGML OGC Standard and the International Standard ISO 19152. Practical implementation of the CityGML-LADM ADE model has demonstrated the benefits of providing relations between spatial objects from legal and physical world. The insight into the third dimension of physical objects helps to understand the location and size of the legal spaces as well as it is relevant in the context of developing the multipurpose cadastral systems.

Ying et al. (2014) provide a framework and workflow for the conversion from CityGML data to 3D Cadastral unit with the test of city data of CityGML LOD3.
Roschlaub and Batscheider (2016) used 3D City Database (3DCityDB[2]) to store the 3D buildings (at LOD2 level), created as a combination of 2D digital building ground plans derived from the official digital cadastral map; and LIDAR (Light Detection And Ranging) data. 3D City Database is a free 3D geo database to store, represent, and manage virtual 3D city models on top of a standard spatial relational database. The database model contains semantically rich, hierarchically structured, multi-scale urban objects facilitating complex GIS modeling and analysis tasks. With a database scheme the user has the possibility to create a CityGML conformant data model in the database. Seifert et al. (2016) add that these data participate in the existing national and international spatial data infrastructure (SDI), for example through simple export to the defined INSPIRE topics (e.g. Buildings).

2.5 Constraints supported

In the introduction the importance of constraints within the Model Driven Architecture (MDA) was emphasized. Now we have a look at the geometric aspect of this. A methodology of modelling 3D geo-constraints has been proposed (Xu et al, 2016) and can be used as a generic approach for all spatial-related constraints specifications in four stages:

1. Natural Language
2. Geometric/Topological Abstractions
3. UML/OCL Formulations
4. Model Driven Architecture (MDA)
    a. Database PL/SQL Code
    b. Exchange Format XML
    c. Graphic User Interface ArcGIS

Natural language is a simple way to specify a constraint statement relating to spatial objects, but it is subjective to the individuals and therefore a more objective specification is necessary. A logical next step is making drawings of the objects (mostly the ‘nouns’ in a sentence) in order to illustrate the shape of the objects. After that, the objects interactions (mostly the ‘verbs’) can be explained better by formal descriptions of topological relationships, e.g. Egenhofer 9 intersection matrices (9IM) (Egenhofer 1989). Constraint statements thus become more specific and clear to others, and not subject to multiple interpretations. In order to let machines understand the constraints and automate the model translation, a further specification should be made considering MDA. UML/OCL as a modelling aid/tool therefore is the clear choice at this stage. Under the support of various tools/software, the constraints implementation in the database (e.g. PL/SQL code), data exchange (e.g. XML schema), graphic user interface (e.g. ArcGIS) or any other domains, can be automated. Here we focus on the constraint implementation in the database. With a small modification the generated code can be used in database triggers, which realises the implementation of constraints checking.

2.6 Standardization

Information models should, whenever possible, be based on agreements and standards. In this manner it is possible to better understand and reuse each other’s data in our networked society. Also standardization brings together the knowledge of experts from around the world. Using a

[2] http://www.3dcitydb.org/3dcitydb/3dcitydbhomepage *(accessed on 21 August 2016)*

standardized information model also imports the expert knowledge. Standards enable interoperability

ISO

ISO is an independent, non-governmental international organization with a membership of 163 national standards bodies[3]. Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges.

The ISO 19100 is a series of standards for defining, describing, and managing geographic information. This standard defines the architectural framework of the ISO 19100 series of standards and sets forth the principles by which this standardization takes place. Standardization of geographic information can best be served by a set of standards that integrates a detailed description of the concepts of geographic information with the concepts of information technology. A goal of this standardization effort is to facilitate interoperability of geographic information systems, including interoperability in distributed computing environments. The ISO 19100 series of geographic information standards establishes a structured set of standards for information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth. This standard specifies methods, tools and services for management of geographic information, including the definition, acquisition, analysis, access, presentation, and transfer of such data in digital/electronic form between different users, systems and locations.

The overall objectives of ISO/TC 211 are (ISO/TC 211, 2009):

- increase the understanding and usage of geographic information;
- increase the availability, access, integration, and sharing of geographic information;
- promote the efficient, effective, and economic use of digital geographic information and associated hardware and software systems;
- contribute to a unified approach to ecological and humanitarian problems.

OGC

The Open Geospatial Consortium (OGC) is a non-profit organization that deals with the development of standards for modelling real-world objects. These standards deal with conceptual schemes for describing and manipulating the spatial characteristics of geographic features. The specification defines three important areas, namely (Khuan et al., 2008):

- Data types: the need to have data types that represent real world object is obvious. Different kinds of data types and different kinds of objects could be modelled within DBMS.
- Functions/operations: there must be functions and operators to support the management of multi-dimensional objects that work for spatial analysis in DBMS.
- Spatial index: the main purpose is to deal with spatial searching (query), and sometimes it is implemented in different spatial operators to speed up the query process.

Cooperation between ISO and OGC

By 1995 ISO/TC 211, developing international standards for spatial data and the OGC, developing computer interface specifications, became highly visible and prominent players on the international geographic agenda. Later ISO/TC 211 and the OGC formed a joint coordination group to leverage mutual development and minimize technical overlap. The OGC

[3] http://www.iso.org/iso/home/about.htm *(accessed on 19 August 2016)*

is submitting their specifications for ISO standardization via ISO/TC 211. Achieving more interoperability requires a proactive coordination of spatial standards at both the abstract and implementation levels. Proactive cooperation among spatial standards activities of ISO/TC 211 and the OGC should also help to use available resources more efficiently by minimizing technical overlap wherever this occurs. Such coordination and cooperation should lead to more market-relevant spatial standards, and could serve as a useful roadmap for all interested parties (ISO/TC 211, 2009).

INSPIRE

The European Union promotes the Infrastructure for Spatial Information in the European Community Directive (2007/2/EC) for a wide range of applications. The Directive sets the legal framework for the establishment of the Infrastructure for Spatial Information in the European Community (INSPIRE). A major task of the INSPIRE programme is to enable interoperability and, when feasible, harmonisation of spatial data sets and services within Europe. Each Member State has to create and maintain a series of spatial data that is organized into three annexes. To ensure that the spatial data infrastructures of Member States are compatible and usable by the Community in a transboundary context, the Directive requires that common implementation Rules are adopted in a number of specific areas (Metadata, Data Specifications, Network Services, Data and Service Sharing and Monitoring and Reporting). INSPIRE is based on selected ISO/TC211 and OGC standards, and complemented among others with detailed data specifications for 34 themes as listed in the three annexes.

3. STANDARDIZED INFORMATION MODELS

3.1 ISO 19152 LADM

LADM is of one of the first spatial domain standards within ISO TC 211. There is a need for domain specific standardisation to capture the semantics of the land administration domain on top of the agreed foundation of basic standards for geometry, temporal aspects, metadata, and observations and measurements from the field. This is required for communication between professionals, for system design, system development and system implementation purposes and for purposes of data exchange and data quality management. Such a standard will enable Geographical Information Systems (GIS) and database providers and/or open source communities to develop products and applications. And in turn this will enable land registry and cadastral organisations to use these components to develop, implement and maintain systems in an even more efficient way. LADM provides a shared ontology, defining a terminology for land administration. It provides a flexible conceptual schema with three basic packages: parties, rights (and restrictions/responsibilities) and spatial units. LADM supports the development of application software for land administration, and facilitates data exchange with and from distributed land administration systems (van Oosterom and Lemmen, 2015). In LADM, 2D and 3D representations of spatial units use boundary face strings and boundary faces as key concepts (see Figures 3 and 4).

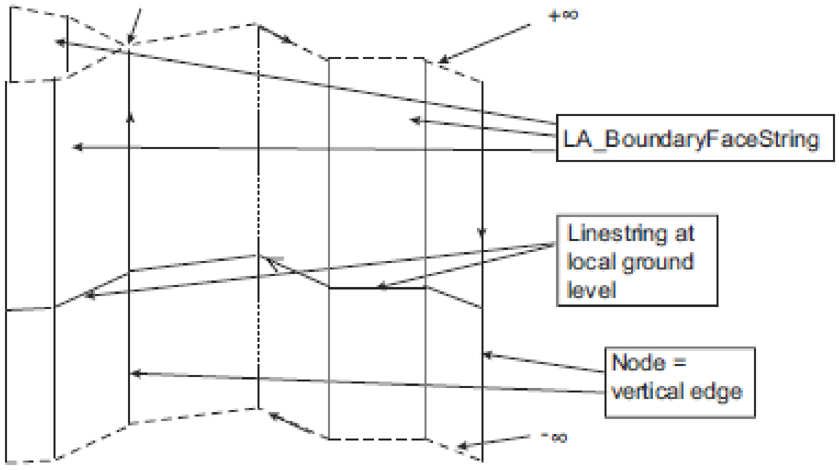

Figure 3. Boundary face string concepts (ISO, 2012)

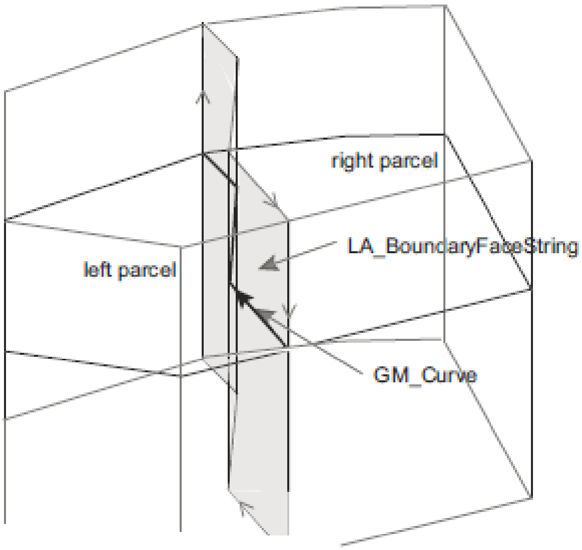

Figure 4. Spatial units defined by boundary face strings (ISO, 2012).

3.2 LADM OWL ontology

The World Wide Web Consortium (W3C) is an international community where Member organizations, a full-time staff, and the public work together to develop Web standards. W3C publishes documents that define Web technologies. These documents follow a process designed to promote consensus, fairness, public accountability, and quality. At the end of this process, W3C publishes Recommendations, which are considered Web standards[4].

The W3C Web Ontology Language (OWL) is a Semantic Web language designed to represent rich and complex knowledge about things, groups of things, and relations between things. OWL is a computational logic-based language such that knowledge expressed in OWL can be

[4] https://www.w3.org *(accessed on 19 August 2016)*

exploited by computer programs, e.g., to verify the consistency of that knowledge or to make implicit knowledge explicit. OWL documents, known as ontologies, can be published in the World Wide Web and may refer to or be referred from other OWL ontologies. The current version of OWL, also referred to as "OWL 2" is an extension and revision of the 2004 version of OWL[5].

The current ISO 19152 - Land Administration Domain Model (LADM) standard (ISO, 2012), being modelled in Unified Modeling Language (UML) with additional explanatory natural text and tables, will facilitate the software development and database design for the proper implementation of land administration systems. The use of UML supports generating a database schema or exchange format (Soon et al., 2014). To support reasoning and inference, Soon (2013) has formalized LADM in OWL. LADM OWL ontology also supports automated integration of land administration information (Boskovic, et al., 2010; Sladić, et al., 2013).

To use the LADM OWL ontology for automated integration of land administration information, Soon et al. (2014) proposed to augment the LADM OWL ontology with the concept of 'Physical Space Building Unit' (see Figure 5). In addition, as a physical building sometimes can have more than one legal boundary (for example through strata subdivision) a relation is defined as *hasLegalSpace* between 'Physical Space Building Unit' and 'Legal Space Building Unit'. The relation *hasLegalSpace* is an ObjectProperty in the LADM OWL ontology. The same also applies to utility network where a new concept 'Physical Space Utility Network' is added. The relation *hasLegalSpace* also links 'Physical Space Utility Network' with 'Legal Space Utility Network' (Soon et al., 2014).

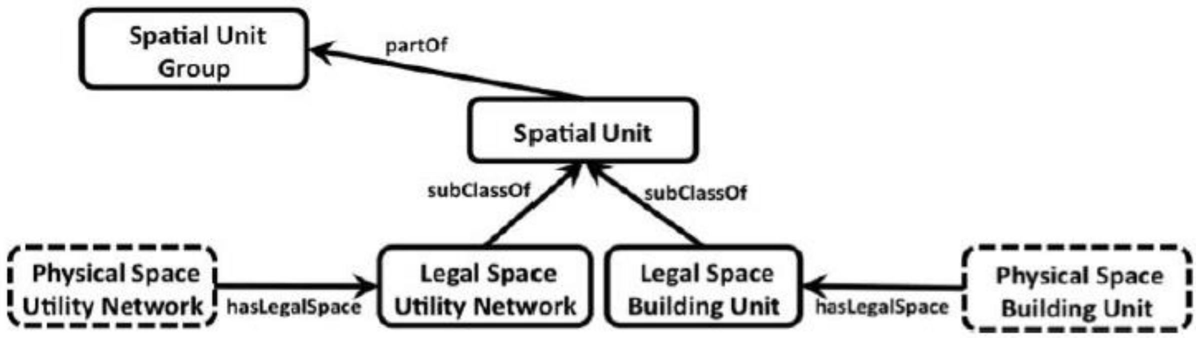

Figure 5. Extension to the LADM OWL ontology with the concept 'Physical Space Utility Network' and 'Physical Space Building Unit' (highlighted in dash-lined boxes) and with a new relation *hasLegalSpace* (Soon et al., 2014)

The addition of new concepts ('Physical Space Building Unit' and 'Physical Space Utility Network') in the LADM, OWL ontology helps to integrate information about building from CityGML and LandXML as discussed in detail by Soon et al. (2014).

3.3 INSPIRE Data specifications on cadastral parcels[6]

Land Administration is a broad topic with many applications, which provide a basic infrastructure for implementing land related policies and land management strategies to ensure social equity, economic growth and environmental protection (Williamson et al., 2010). The

[5] https://www.w3.org/OWL *(accessed on 19 August 2016)*
[6] This section is largley based on Psomadaki et al. (2016).

European Union, acknowledging that LA can contribute to sustainable development and thus environmental policy, included ‘Cadastral Parcels’ in ISNPIRE.
Cadastral parcels (INSPIRE TWG-CP, 2009) are described in Annex I of INSPIRE Directive and are thus considered as reference data. The data specifications focus only on the geometrical aspects of cadastral parcels while information about ownership and other rights are outside its scope. The temporal alignment in the development of LADM and INSPIRE’s ‘Cadastral Parcels’ (CP), led to the development of compatible definitions and common concepts in both models (ISO 2012). The LADM-based model version of CP is included both in the ISO19152 publication (Annex G) and in the Data Specifications of CP (Annex C). However, their differences are immediately noticeable as the latter focusses on the geometric aspect, not taking into consideration the rights, restrictions and responsibilities applied to it**.**
The application schema of cadastral parcels consists of four entities; see Figure 6. The core – and always available – entity of the cadastral parcels schema is the ‘Cadastral Parcel’. The other three entities are ‘Cadastral Zoning’ (the intermediary areas used to divide the national territory into cadastral parcels), ‘Cadastral Boundary’ (part of the outline of a cadastral parcel) and ‘Basic Property Unit’ (the basic unit of properties which may consist of one or more parcels). Each entity consists of three kinds of attributes: the obligatory, the voidable and the information about time (also voidable). The voidable characteristics in the INSPIRE context are “those properties of a spatial object that may not be present in some spatial datasets, even though they may be present or applicable in the real world”.
The “Cadastral Boundary’ class will be available from the member state only if information about the absolute positional accuracy information is recorded for the boundary. Furthermore, ‘Basic Property Units’ will be used by countries where cadastral references concern basic property units. The INSPIRE ‘Cadastral Parce’l model is basically a subset of LADM with specific choices for representing parcels (Annex G of ISO 19152). However, in this case, other themes of the INSPIRE seem to be very much related to the LADM. For example, ‘Addresses’ is considered an external class in LADM and it is expected that there exists a detailed model (data specification) and registration to which can be referred. Within an SDI setting, the various registrations can refer to each other. This is also true for buildings and administrative units. For example, in the INSPIRE themes, the municipalities are considered part of the ‘Administrative Units’ theme and therefore they are not repeated in ‘Cadastral Zoning’. It is expected that the related datasets are harmonised with each other.
Besides not covering RRRs and Parties, other aspects outside the scope of INSPIRE’s CP are the survey (spatial source) information and 3D representations (just 2D is supported). Only INSPIRE’s data specification for buildings do support 3D representations.

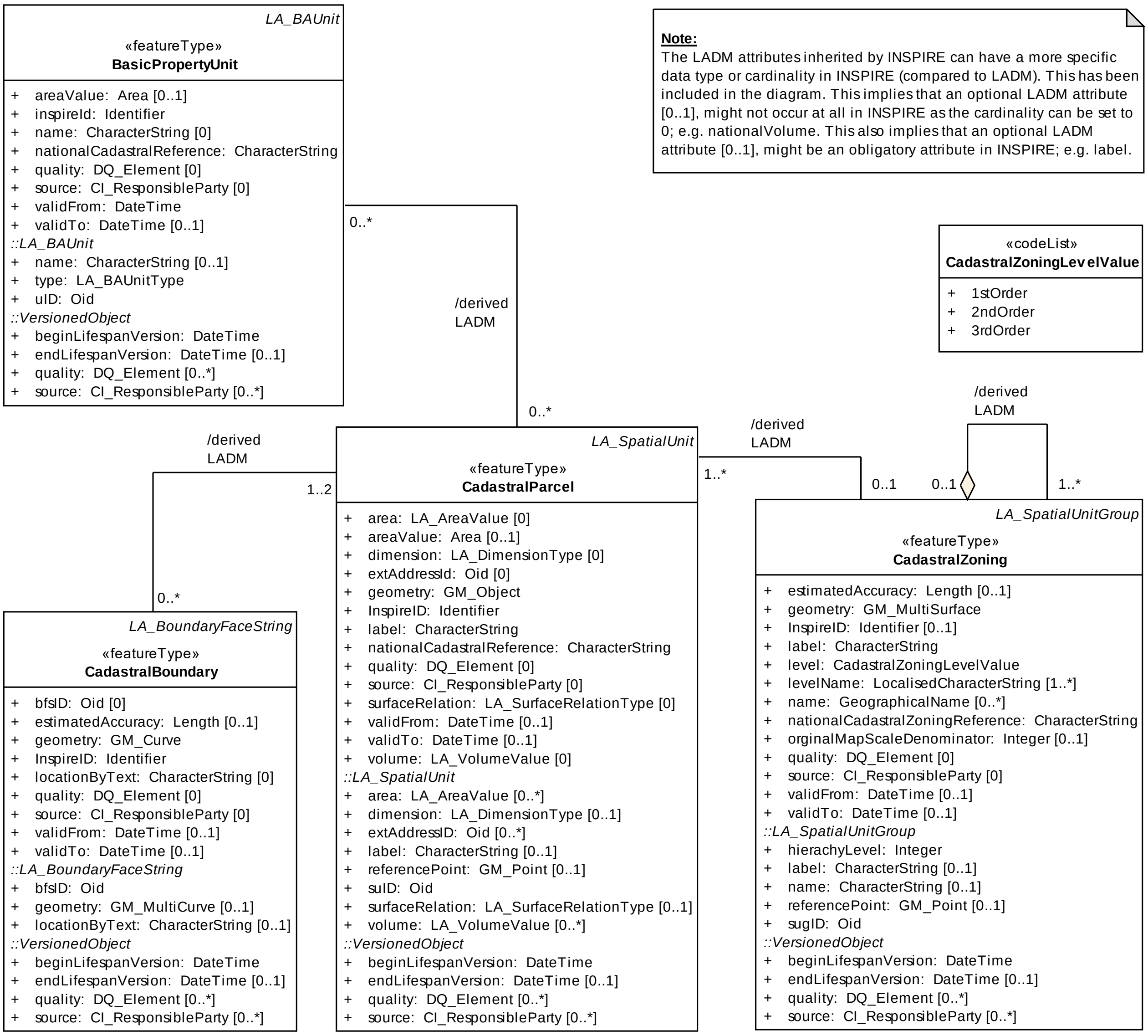

Figure 6 The INSPIRE cadastral parcel model based on the LADM (from Annex G, ISO 19152)

3.4 GML

GML is an XML grammar defined by OGC to express geographical features (ISO, 2007). GML serves as a modeling language for geographic systems as well as an open interchange format for geographic transactions on the Internet. As with most XML based grammars, there are two parts to the grammar – the schema that describes the document and the instance document that contains the actual data. A GML document is described using a GML Schema. This allows users and developers to describe generic geographic data sets that contain points, lines and polygons. However, the developers of GML envision communities working to define community-specific application schemas that are specialized extensions of GML. Using application schemas, users can refer to roads, highways, and bridges instead of points, lines and polygons.

Aien et al. (2014) convert the logical data model of the 3D Cadastral Data Model (3DCDM) to a physical data model. The physical data model of the 3DCDM has been developed as an application scheme of the GML (in version 3.2.1). For this purpose, eleven XML schemes were developed: 3DCDM Root, LegalPropertyObject, InterestHolder, Survey, CadastralPoints, Building, Land, Tunnel, UtilityNetwork, PhysicalPropertyObject, and Terrain.

3.5 CityGML

There are many formats for the storage and visualization of spatial data, however they are usually focused only on a description of geometry. In contrast, the CityGML which provides a geographic information model for urban landscapes, not only represents the shape and graphical appearance of the 3D city objects, but also addresses the representation of the semantic and thematic properties, taxonomies and aggregations (Góźdź et al., 2014).

Open Geospatial Consortium has defined CityGML (City Geography Markup Language) for modeling 3D city models. The current version of CityGML is 2.0 and contains modules like 'Relief', 'Building', 'City Furniture', 'Water Body', 'Bridge', 'Tunnel', 'Vegetation', 'Land Use', and 'Transportation'. CityGML defines classes, attributes and relations for topographic features with aspects of geometrical, topological, semantic and appearance. Different level of details can be captured from LOD 0 to LOD 4. LOD 0 represents the earth surface (i.e. the terrain) be it as Digital Terrain Model (DTM) or Digital Surface Model (DSM). LOD 1 represents topographic and constructed features as simple 3D blocks (i.e. no texturing or appearance). LOD 2 shows topographic features with texturing and refined top structure. In the case of a building, for example, instead of a flat roof surface in LOD 1, LOD 2 models the actual shape of a rooftop. LOD 3 models more detailed topographic features and includes other external installations – for example windows and doors. LOD 4 includes internal installation modeling (van den Brink et. al., 2012).

In the 'Building' module of CityGML, 'Abstract Building' is an important class, which has two subclasses called 'Building' and 'Building Part'. The attributes for the 'Abstract Building' class include 'Class', 'Function', 'Usage', 'RoofType', 'MeasuredHeight', etc. The 'Abstract Building' class also has geometries, which support the level of details from LOD 0 to LOD 4. As 'Abstract Building class' specializations, 'Building' and 'Building Part' inherit all attributes and relations of 'Abstract Building' (Soon et al., 2014). The CityGML schema can be extended to have additional modules such as 'Cadastre' using the Application Domain Extension (ADE) (Stoter et al., (2011); van den Brink et al., (2012); Góźdź et al., 2014).

3.6 LandXML/InfraGML

There are currently two transport specifications in discussion for the interchange of survey plan data: 1: LandXML which is currently in use in New Zealand and being implemented in Australia and Singapore; and 2: InfraGML which is being developed by the OGC as a BIM interchange specification and as successor of LandXML for survey data (Thompson et al., 2016). LandXML can also be used for capturing other types of engineering data, such as pipe networks and roadways (Soon et al., 2014). Soon et al. (2014) extend LandXML to model 3D parcels and introduce the Nested Parcels Approach, which makes use of the element of PntList3D of LandXML, to store 3D coordinates.

In addition to LandXML, the expression in InfraGML (currently in development by the Open Geospatial Consortium) (Scarponcini 2013; OGC 2016) should be considered for the integrated footprint (LA_BoundaryFaceString) and face (LA_BoundaryFace) volumetric encoding of spatial units (Thompson et al., 2016).

Apart from the transport of survey data there may be a need for transport of parameters related to transformations applied to sets of (2D or 3D) points. This may be needed if separate software

(in separate hardware – eg survey instruments) is used for adjustments of observations. This type of adjustments is also needed in a 3D environment.
Integrating data from different sources means integrating data with different object versions to new objects in a new or existing environment – this had impact on the organisation of data exchange.

3.7 IndoorGML

IndoorGML was adopted as an OGC standard in December 2014 (Lee et al 2014, Li, 2016). IndoorGML is intended to support development of indoor navigation systems, by providing description of indoor space and GML syntax for encoding geoinformation (geometry, network or path) for indoor navigation. In this respect IndoorGML is application-oriented standard and differs from generic 3D standards such as CityGML, KML, and IFC. It is based on subdivision of the interior space. The obtained cells are described with the geometry, semantics and topology that are important for indoor navigation. In this respect, IndoorGML can be seen as a complementary standard to CityGML, KML, and IFC to support location based services for indoor navigation. IndoorGML defines the following information about indoor space: navigation context and constraints, space subdivisions and types of connectivity between spaces, geometric and semantic properties of spaces and navigation networks (logical and metric), and their relationships.

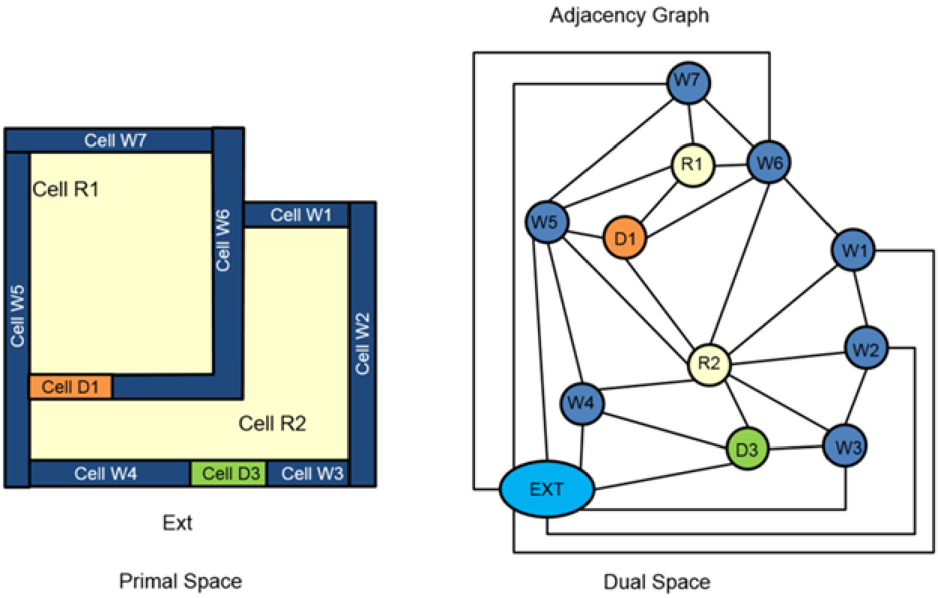

Figure 7. Example of spaces in a building: a) non-navigable (in blue) and navigable (in yellow, orange and green) b) derived network

The notion of space or 'cell' is the most important concept in IndoorGML (Figure 6). A building or groups of buildings are subdivided into non-overlapping cells. The cells are further classified into navigable or non-navigable. The adjacency network is then to be derived by applying Poincaré duality, i.e. each cell in the 3D space (named also primal space) is mapped in a node in 2D space (dual space) and the adjacency between the spaces represents the edges. For the purpose of navigation, non-navigable spaces are not of interest and have to be excluded from the adjacency network (not illustrated in Figure 7b). Considering the remaining links and the semantics of the spaces (i.e. which spaces are doors), the navigation/connectivity network is derived. An important characteristic of the IndoorGML is that cells do not need to be bordered

by physical features. Cells can be defined as aggregation of features or a physical space can be subdivided into smaller units. It is also possible to neglect the size of some physical features, e.g. doors, windows. As visible on Figure 7, the doors are represented as spaces, but the standard allows to consider them as borders (i.e. 'thin doors') between two spaces. In that case there are no door nodes in the navigation network.
IndoorGML allows multiple space subdivisions per building (Figure 8). A space subdivision can be derived from the topography of the building, the function of spaces, the security restrictions, but can be also with respect to coverage of sensors such as wifi or RFID (Radio-frequency identification) or the legal (LADM RRRs) status of spaces. Different spaces are to be organized according the Multi-Layered Space Model (Becker et al 2008).

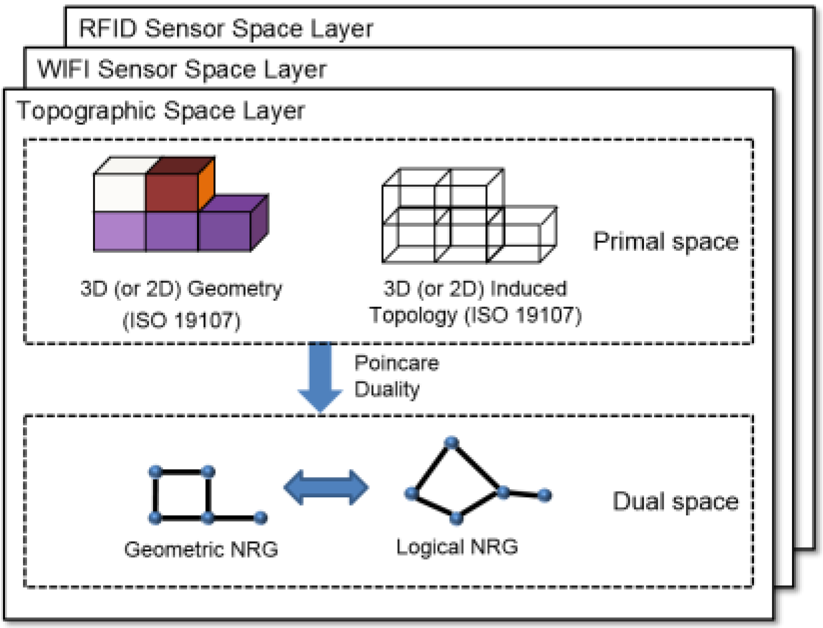

Figure 8. Multi-Layered combination of alternative spaces (Lee et al 2014)

Space modelling with respect to its legal use is specifically interesting for IndoorGML. Restrictions, rights and responsibilities on a part of a floor or a building can influence the accessibility and can significantly change the set of cells that can be used to derive a network. Many office buildings share common entrance and registration areas and they share the responsibilities for the maintenance of the common area. Shopping malls may also share access to different departments and sections but they also have clearly defined area which are given for use only to them. In many public buildings, restricted or security areas are clearly identified by requiring security cards and/or security doors. Such RRR are rarely identified with physical boundaries and are usually difficult to model.

3.8 BIM/IFC

ISO 16739:2013 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, specifies a conceptual data schema and an exchange file format for Building Information Model (BIM) data (ISO, 2013).
Under development is ISO/AWI 19166 Geographic information -- BIM to GIS conceptual mapping (B2GM) [7]. This international standard defines the conceptual framework and

[7] http://www.iso.org/iso/catalogue_detail.htm?csnumber=32584 (*accessed on 19 August 2016*)

mechanisms for the mapping of information elements from BIM to GIS to access the needed information based on specific user requirements. The conceptual framework for this mapping is defined with the following three mechanisms:

- BIM to GIS Element Mapping (B2G EM);
- BIM to GIS LOD (Level of Detail) Mapping (B2G LM);
- BIM to GIS Perspective Definition (B2G PD).

The conceptual mapping mechanism defined in this international standard uses existing international standards such as Geography Markup Language (GML), CityGML (OGC standard) and Industry Foundation Classes (IFC).

3.9 Linking IndoorGML and LADM[8]

In this section we investigate the possible synergy between two different but related standards: OGC's IndoorGML and ISO TC211's LADM. Both (can) deal with 3D spaces with properties, constraints and associations attached and both can operate with abstract notations of space. But there are also differences, e.g. LADM is just a conceptual model, while IndoorGML is also an actual XML schema (technical model), which can be used directly for data exchange and storage. Also, the scope is different; e.g. IndoorGML focuses on indoor spaces, while LADM addresses all spaces (in principle a complete subdivision of the countries territory, including outdoor, water, surface and subsurface spaces). LADM models legal and administrative concepts such as use and ownership rights of spaces related to certain parties. IndoorGML puts emphasis on connectivity of spaces related to the navigability as one of the main use cases. These characteristics make the two standards quite complementary and this motivates our exploration in the combination of both.

The spaces defined by LADM are the results of legal/administrative rights, restrictions and responsibilities (as the largest possible spaces, homogeneous with respect to these RRRs). The space subdivision of IndoorGML is based on navigable areas and their connectivity. IndoorGML also recognizes other spaces, called abstract spaces. This section will compare the space characterizing of the two models and will explore options to combine the models. Many indoor applications deal with abstract spaces, i.e. spaces which do not have well-defined physical boarders (such as walls, ceiling and floors), to identify a function, use or right on the space. For example, a room can be further subdivided into several sub-spaces indicating 'information corner', and 'working area', or a 'security area'. Figure 9 illustrates such examples. Such functional areas need to be identified and usually this is done by applying geometric or semantic approaches for partitioning of space (Bandi. and Thalmann, 1998, Becker et al 2008, Goetz and Zipf, 2011, Khan and Kolbe 2012, Afyouni et al 2012, Brown et al 2013, Zlatanova et al 2013, Kruminaite and Zlatanova, 2014). Although the importance of such spaces is recognized, their modelling is still insufficiently explored, especially in the context of human perception and human navigation (Fallah et al, 2013). By contrast, the LADM may need to represent a completely inaccessible volume of rock through which a tunnel may be constructed in the future.

[8] This section is based on (Zlatanova et al, 2016) and (Abdullah et al, 2017)

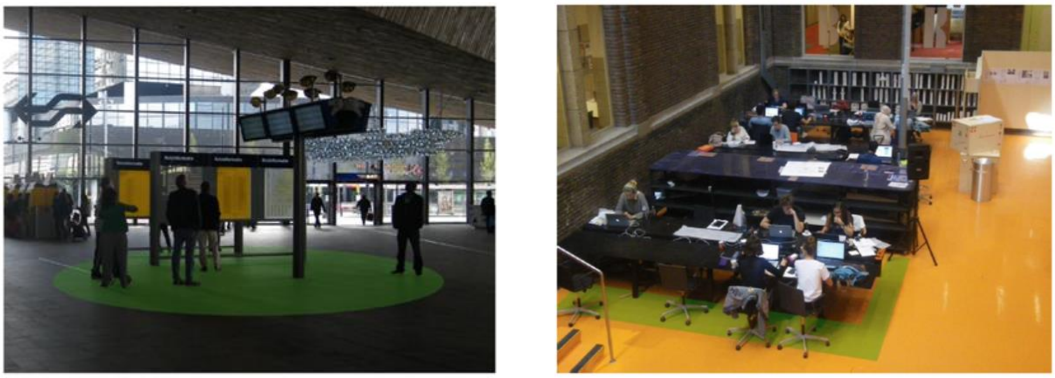

Figure 9. Examples of functional areas (in green): information corner and working area (Kruminaite and Zlatanova, 2014)

Modelling is always within a certain domain and scope, despite the fact that many concepts are linked to other external concepts. In the past, the conceptual models of LADM and European Union's Land Parcel Identification System (LPIS) have been linked (Inan et al, 2010) as it makes sense to combine the information of cadastral parcels (LADM) to agricultural parcels (LPIS). LPIS mainly concerns 'outdoor' parcels. For the (extended) indoor environment it does make sense to combine the conceptual models of IndoorGML and LADM. With this, information from these two domains can be used together in a meaningful manner. Actual use cases include:

- Airports – common spaces accessible for all visitors, check in area, passport control, waiting/shopping areas, boarding gates, transit areas and so on.
- Hospitals – common access areas, examination sections, areas for hospitalized persons, surgery, laboratories, storage of medical equipment, etc.
- Museums - exhibition halls, storage halls, administration areas, security areas.

Summary – Combined use of LADM and IndoorGML models

The two standards have been developed for different purposes (navigation vs. land administration) and have different scope (indoor vs. indoor/outdoor, above/below surface). The two standards have many differences and similarities. The main similarities between the two models are:

- Both models (can) deal with semantically annotated 3D spaces, which have properties.
- Both models operate with abstract spaces. Abstract spaces in IndoorGML can be defined on the basis of user or environment properties. Abstract spaces in LADM are based on legal regulations. Similarly, IndoorGML allows subdivision and aggregations of spaces such as accessibility, security, etc. The same is true in LADM: legal spaces can be grouped in LA_BAUnit or LA_SpatialUnit andvorganized in a hierarchy.
- Both models have a notion of primal space with geometry and topology. The 3D partitioning of LADM can be seen as primal space. LADM maintains links to external classes of which some are mentioned in annex K of the standard: building units, utility networks. IndoorGML provides links to CityGML, IFC and KML.
- Both models can support several subdivisions of space. The mechanism in IndoorGML is by defining specific space layers. LADM abstract subdivisions are embedded in the conceptual schema (and called LA_Level).
- Both models maintain relationships between objects. LADM supports extensive set of relationships and constrains. Spatial relationships can be based on topology but could be

also without topology (just geometry or even textual descriptions). IndoorGML does not have specific notions of constraints between objects, but rather topological relationships (i.e. adjacency and connectivity) is used to derive the dual space.

There are also a number of significant differences:

- LADM is only a conceptual schema, while IndoorGML has XML implementation.
- IndoorGML requires non-overlapping subdivision of spaces, LADM may have overlapping abstract spaces, but spatial units related to full ownership may not overlap with each other (these might overlap with a spatial unit defining a restriction; e.g. because of an environmental protection zone).
- IndoorGML maintains primal and dual space, while LADM has only primal space.
- LADM models legal and administrative concepts such as ownership rights of spaces related to certain (group) parties. IndoorGML might use such rights to specify subdivision, but no explicit Space Layer have been developed so far.

LADM could be applied to determine a framework for space subdivision. Thus, the topological primal spatial units do not have gaps or overlaps in the partition in LADM. The rights, restrictions and responsibilities and the administrative unit play a critical part during this process. We explore the combined use IndoorGML and LADM by creating a link that connects each navigable space of IndoorGML to the corresponding LA_SpatialUnit of LADM without adjusting IndoorGML and LADM. As a navigable space in IndoorGML can correspond to various spatial units of LADM (and vice versa), a many-to-many association is needed. In this way, it is possible to model or to subdivide the spatial units in LADM. Via LA_BAUnit the associated rights and parties can be obtained (for navigable spaces linked with a LA_SparuialUnit). Note that in order to be able to use one-to-one correspondence, each space of IndoorGML would needed to be defined based on the constraints of the spatial unit of LADM, and vice virsa. This is considered less convenient.

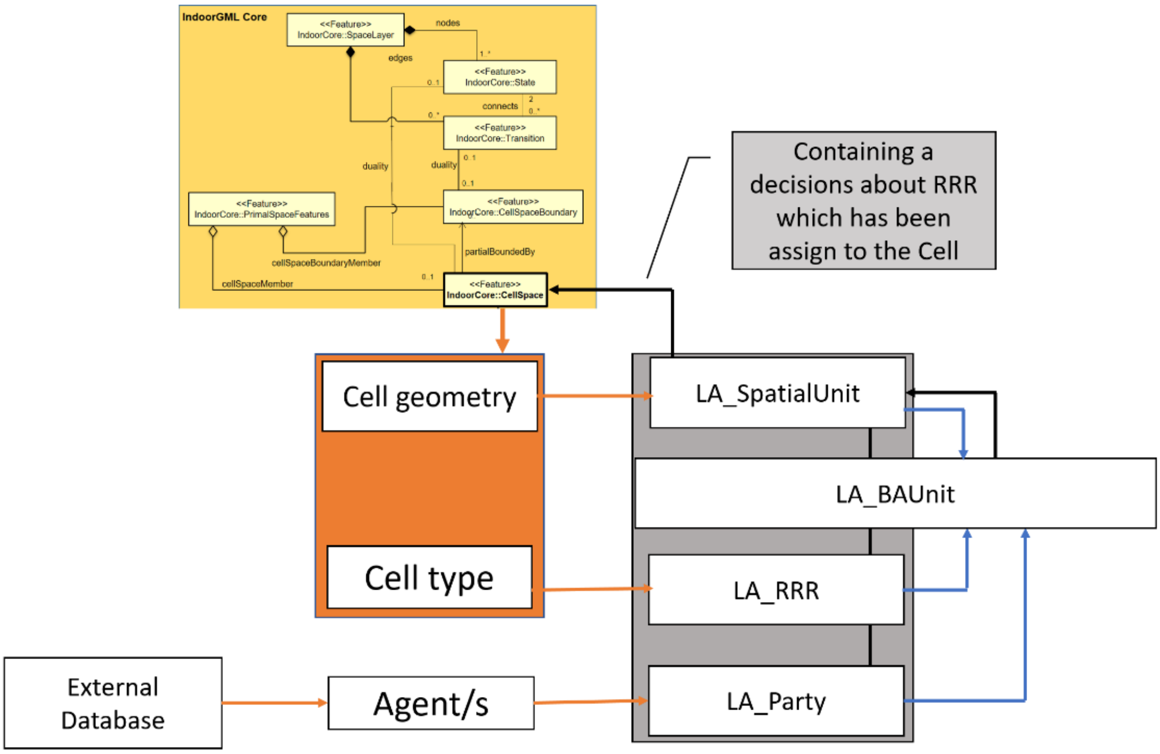

Figure 10. The integration process for IndoorGML and LADM

The rights, restrictions, and responsibilities affect the motion of users (use, manage, transfer, add, receive) in indoor spaces by regulating the access and use of space. Figure 10 represent a general overview of the integrated model of LADM, IndoorGML, and an external party database. IndoorGML associates spatial data that contains information about the geometry of the cells and the external database associates information about users. LADM associates the subdivision of the indoor space to IndoorGML based on the rights, restrictions, and responsibilities.

The major link between the spatial features of indoor space from the ‘Cell Space’ in the IndoorGML with the LA_SPatialUnit package in LADM is modelled as an association. The association provides the identification (Cell number) and the function of the cell. The spatial information of the cell collected by LA_SpatialUnit and the cell function information gathered by the LA_RRR which is a class of the Administrative package. The user’s information in the external database is associated with the LA_Party package. The LA_BAUnit which is a class in the Administrative package will collect the Information to be registered based on the information of each package. Based on registration of information LA_BAUnit and LA_SpatialUnit associate the subdivision of space to the Cell space in IndoorGML.

4 3D LADM COUNTRY PROFILES

In the last few years several prototypes of 3D LADM based country profiles have been developed, for example: Russian Federation (Elizarova et al 2012), Poland (Góźdź and Pachelski 2014), Malaysia (Zulkifli et al., 2014; Zulkifli et al., 2015b), Israel (Felus et al., 2014), Greece (Kalogianni et al, 2016), Trinidad and Tobago (Griffith-Charles and Edwards,

2014) and Turkey (Alkan and Polat, 2016). The first five are elaborated on a bit more in the subsections below.

4.1 Russian Federation

At present, the system of state cadastre and real estate registration is based on the 2D representation of objects including land parcels, buildings and structures. However, the current approach does not cover all situations of the real 3D world (Elizarova et al 2012). Examples of such situations impeding cadastre and rights registration are: multilevel complexes, intersections of various objects in space, underground and elevated engineering networks, etc.
The developed conceptual 3D-cadastre model is based on the ISO 19152 LADM. The model was adapted to the Russian environment and oriented to 5 types of property objects (land parcels, buildings, premises, structures and unfinished construction projects); see Figure 11. Coming from the 2D cadastre and registration system existing in Russia, the option of a polyhedral legal 3D cadastre based on the representation of 3D objects as polyhedrons (volumes limited by flat faces) was selected as a working model. Curved surfaces of such objects as pipelines and cables are approximated by multi-polylines with diameters. For technical implementation, a solution involving the existing 2D portal and linking it with a new 3D-Viewer was selected. This solution is the most lightly implementable and requires minimal changes, based on functionality supported by the existing 2D portal. For the development of the prototype and its testing on the cases, a package of data was acquired and processed according to requirements of the prototype, including:

- a topographic base map and a digital terrain model;
- cadastral data including boundaries and characteristics of cadastral blocks (groups of cadastral parcels) and land parcels;
- information on state registration of land parcels, buildings, premises and structures;
- technical documentation including technical passports with floor plans, etc.

In order to optimise the 3D cadastre prototype using floor plans and additional information, 3D models of buildings were developed reflecting volume characteristics of premises with the concurrent representation of respective right holders in different colours (see Figure 12).

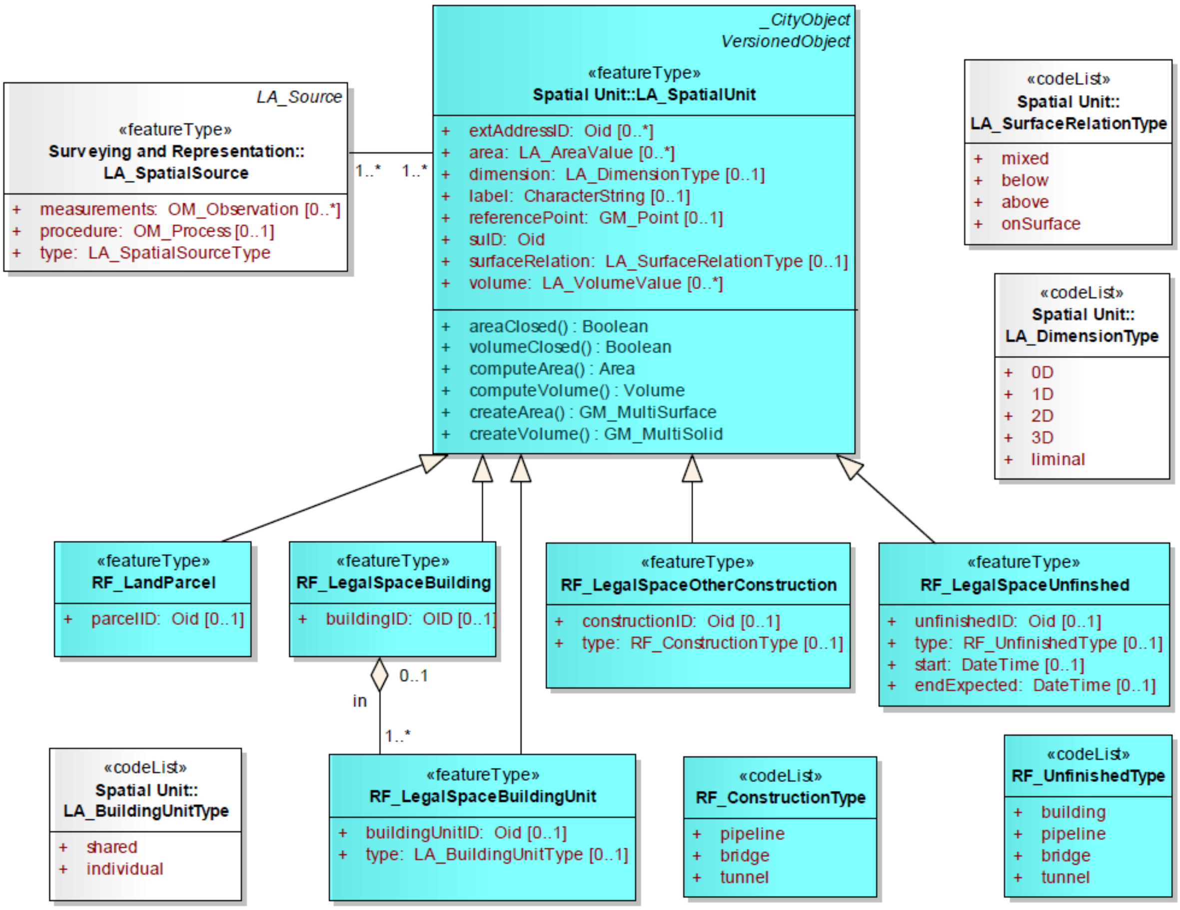

Figure 11. The initial Land Administration Domain Model (LADM) for the 3D cadastre pilot project in the Russian Federation (Vandysheva et al, 2011)

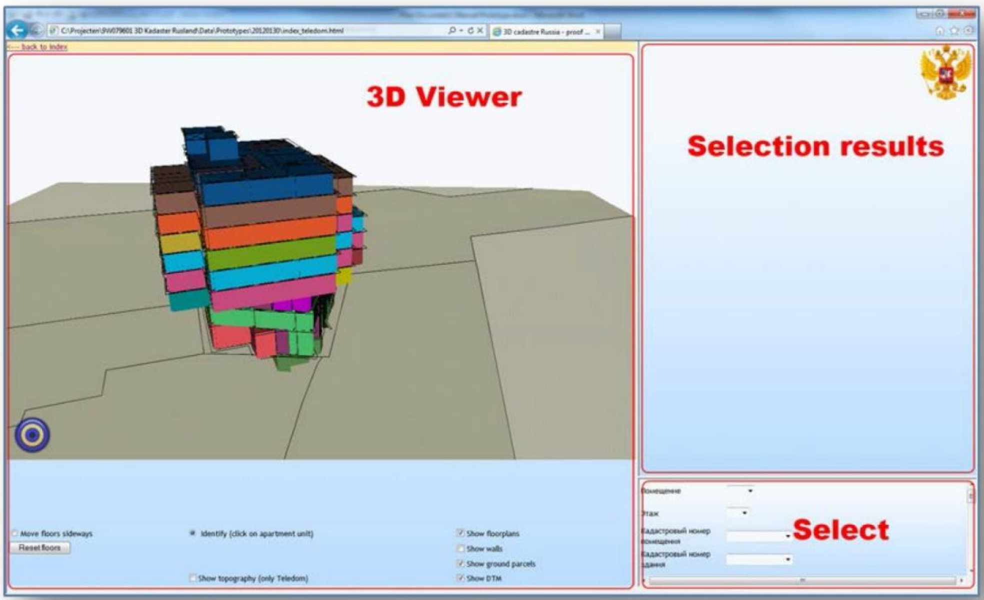

Figure 12. The web-based user-interface to interact and query 3D cadastral objects

4.2 Malaysia

A conceptual model as well as the associated technical model for the 2D and 3D objects have been proposed and developed for Malaysia (Zulkifli, Rahman, van Oosterom, 2014). For both private and public land, the main subdivision of land in Malaysia is based on lots. In many continental European countries, 'lot' would be called 'parcel', but 'parcel' has other meaning in Malaysian context. The lots can have 2D or 3D representations. The Strata Title Act and Strata Management Act are very important for a large part of the Land Administration in Malaysia, and this is especially true for many 3D related situations. The Malaysian LADM country profile includes support for these strata objects: building and building parts (all in 3D within a single lot), land parcel (with house no more than 4 stories within a single lot), accessory unit, and (limited) common property unit including support for provisional and multilayer/underground aspects. In addition, the Malaysian country profile also supports the legal spaces for utilities. By developing a Malaysian country profile based on the international standard ISO 19152, the possible confusion related to terminology (e.g lots, parcels, strata, 2D, 3D) has been resolved. This is not only important for Malaysia, but also useful for many other countries, that have the strata title system.

Figure 13 illustrates the various types of strata objects in Malaysia. A parcel in relation to a subdivided building, means one of the individual units comprised therein (apartment or condominium), which is held under separate strata title. An accessory unit means a unit shown in a strata plan, which is used or intended to be used in conjunction with a parcel. A common property means so much of the lot as is not contained in any unit (including any accessory unit). A limited common property means common property designated for the exclusive use of the owners of one or more strata lots. A land parcel means a unit delineated within the lot (in which is contained a building of not more than four storeys) which is held under a strata title and which may have shared basement, accessory unit and common property.

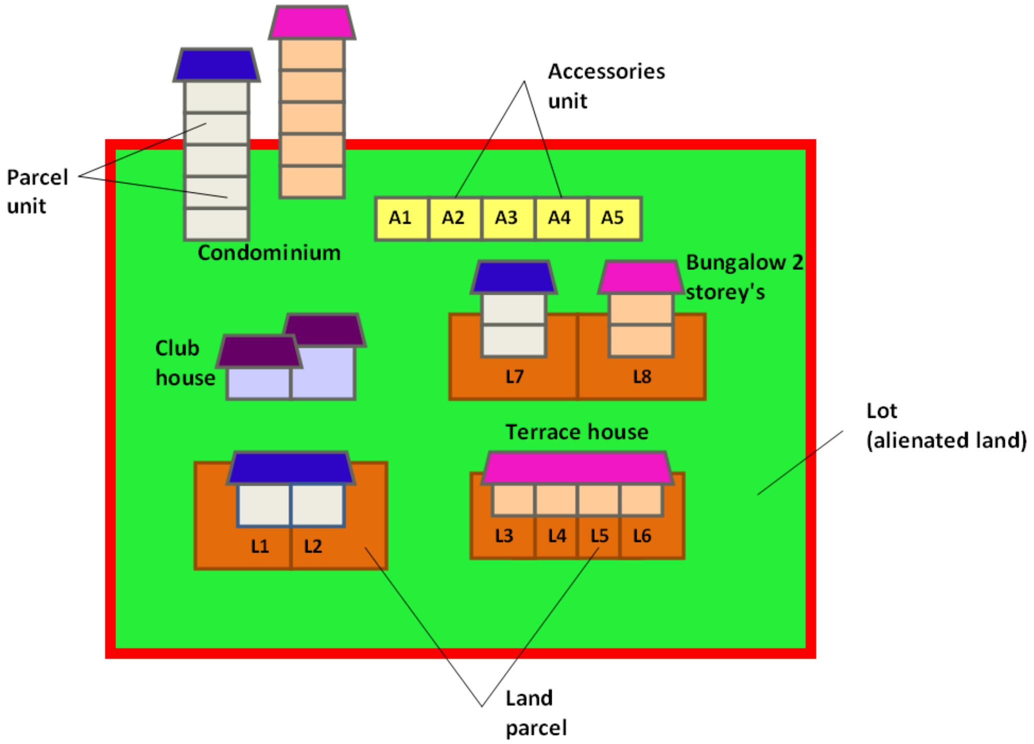

Figure 13. Various cadastral objects related to strata titles within a lot

All classes in the Malaysian country profile are based on the inheritance of the LADM classes - the 'MY_' is the prefix for the Malaysian country profile, covering both the spatial and administrative (legal) data modelling. To illustrate the inheritance from the LADM classes, the MY_classes have either in upper right corner the corresponding LA_class name in italics or have the explicit inheritance arrow shown in the diagram (see Figure 14).
The country profile that has been developed for the 3D spatial unit represents building, utility and lot. The building is represented by MY_Building class and utility represented by MY_Utility class. Both MY_Building and MY_Utility are subclasses of MY_Shared3DInfo (a specialization of LADM's LA_SpatialUnit), containing common attributes such as a GM_Solid geometry attribute, a variable length volume attribute with at least one LA_VolumeValue and a Boolean attribute indication whether the object is provisional or not. Meanwhile, a 3D lot is represented by MY_Lot3D, which is a subclass of MY_GenericLot (which is in turn also a subclass of LA_SpatialUnit). MY_GenericLot has another subclass called MY_Lot2D. Both MY_Shared3DInfo and MY_GenericLot are abstract classes and do not have any instances. Figure 14 illustrates the associated spatial component (with strata classes in darker colour).

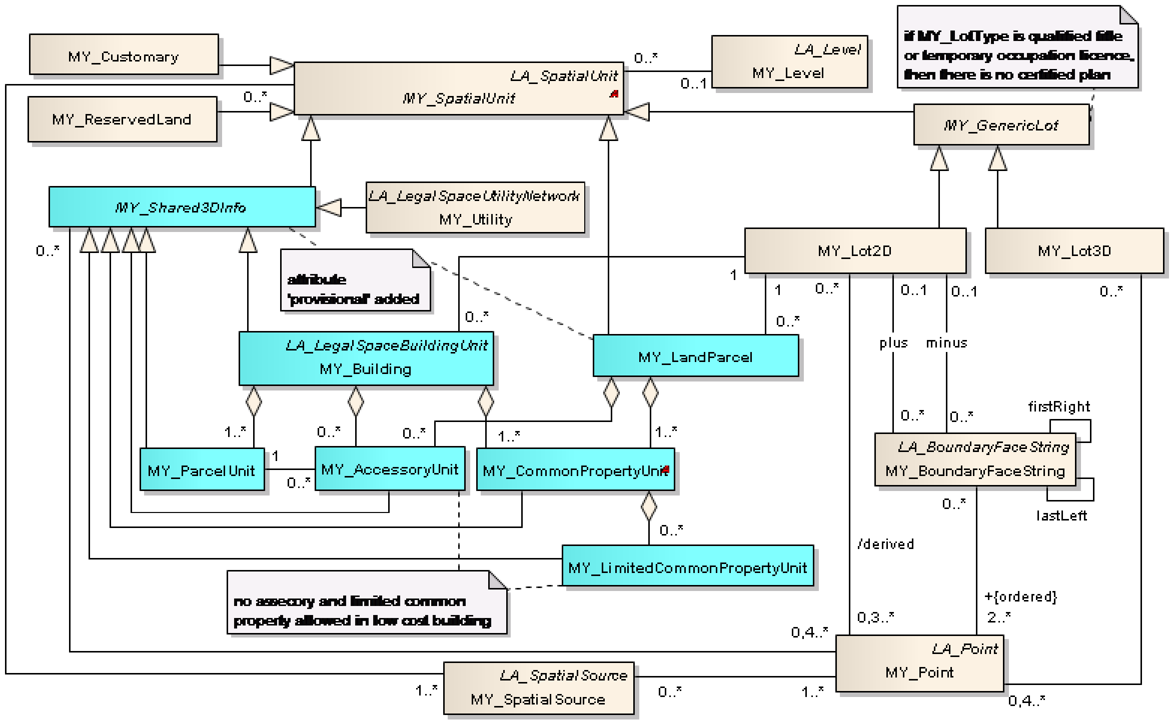

Figure 14. Overview of spatial part of Malaysian LADM country profile (darker colour indicates strata classes)

4.3 Israel

Israel has already quite a long track record in exploring 3D Cadastre solutions. It is therefore wise to remember the earlier recommendations of which the main two aspects are (Shoshani, Benhamu, Goshen, Denekamp and Bar 2005): 1. Appropriate legislation and regulation, 2. 3D sub-parcel principle as guidance for 3D cadastre; see Figure 15. The 3D sub-parcel concept is based on subdivision of the unlimited column of space implied by the 2D surface parcel into at least one completely bounded 3D volume and a remaining (unlimited) space. The bounded 3D volume is within the column of the 2D surface parcel. This approach fits relatively well in the current approach with some extensions. In addition, the recommendations also included more

detailed suggestions as to how to represent the third dimension (analytical x,y,h coordinates with h absolute, that is in orthometric heights above or below sea level) and 3D sub-parcel numbering (extension of current block and parcel number with additional sub-parcel sequence number).
The logic behind the sub-parcel is clear: the owner of the surface parcel (3D column of space) splits the owned space and sells one part to another party. For long infrastructure type of objects the result is that one object, such as a tunnel, is to be represented with many 3D subparcels. To each of the 3D sub-parcels the same right and party should be attached, both initially, but also in future transactions (e.g. tunnel is sold to a company). This is redundant information and error prone. It is better to allow 3D parcels crossing many surface parcels. They should be created in one transaction involving all surface parcels, each selling a part of their property, to create a single 3D subsurface parcel to which the right and party can be attached (for the tunnel).

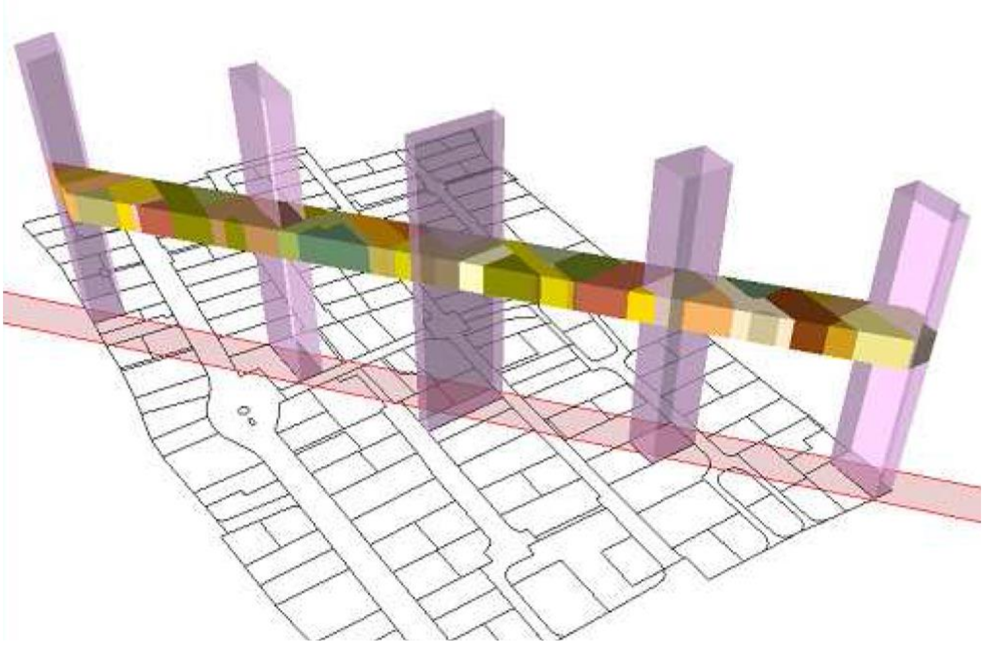

Figure 15. 3D Presentation of the spatial sub-parcels on the background of the existing land parcels. Source: (Shoshani, Benhamu, Goshen, Denekamp and Bar 2005)

Figure 16 shows a UML diagram of the current registration in the initial Israeli country profile as specialization of LADM. The prefix 'IL_' is used to indicate the fact that this is the Israel country profile. The following inheritance relationships are shown IL_Parcel (from LA_SpatialUnit), IL_ParcelArc (from LA_BoundaryFaceString), IL_ParcelNode (from LA_Point), IL_Gush (from LA_SpatialUnitGroup), and IL_Talar (from LA_SpatialSource). The first step towards 3D parcels is the introduction of the 3D IL_BoundaryFace (from LA_BoundaryFace).

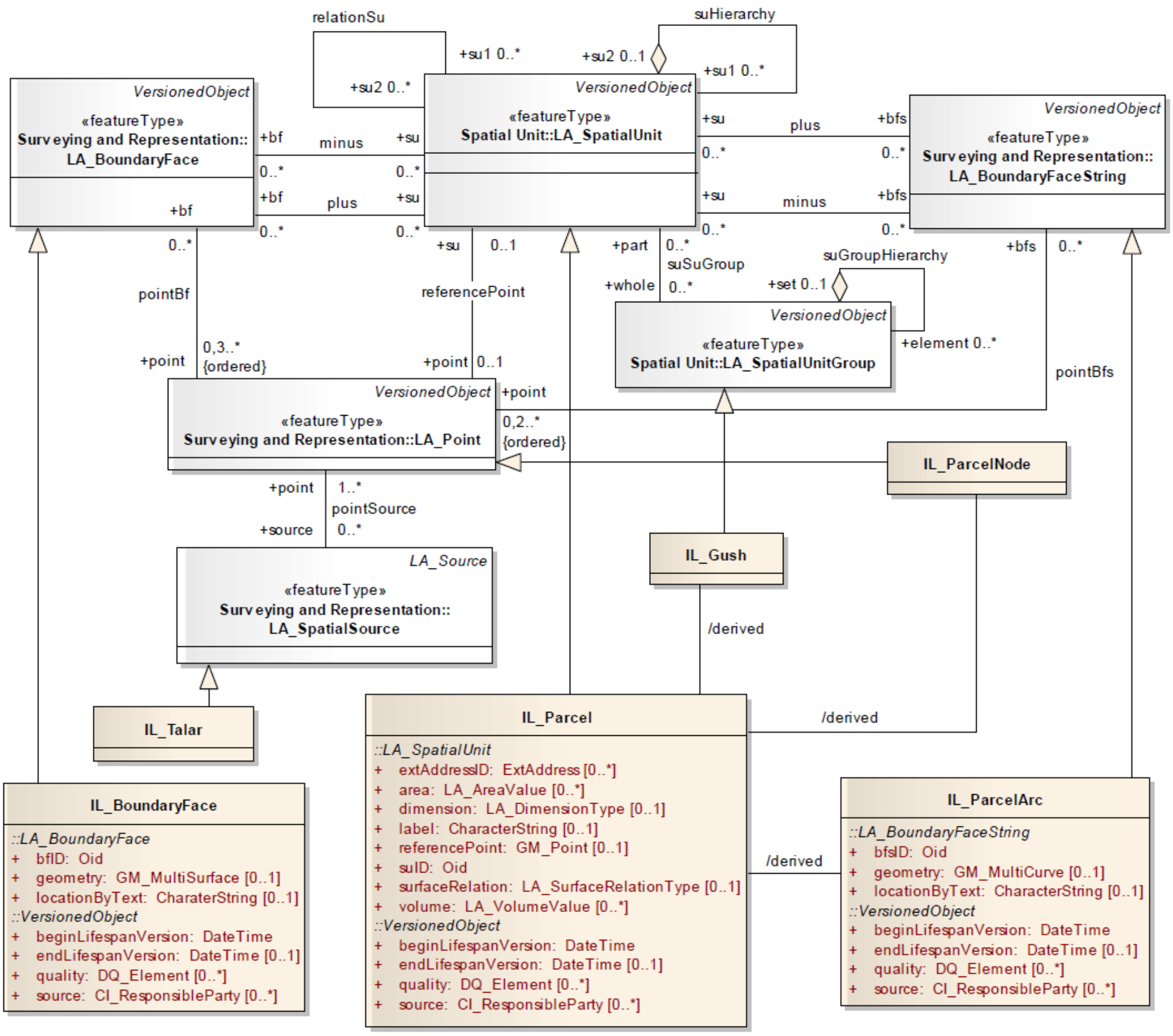

Figure 16. UML model of the initial Israeli country profile as specialization of LADM

4.4 Greece

The massive developments and uses of high-rise buildings indicated that the demand for use of space above and below the ground surface is rapidly increasing in recent years also in Greece. The existing cadastral model does not cover the need for 3D and does not conform to international standards (Kalogianni, Dimopoulou and van Oosterom, 2015). The proposed Hellenic LADM country profile is considered as an effort for overcoming previous shortcomings, introducing a model based on international standards, including the wide range of different types of spatial units, organized in levels according to the LA_Level structure of ISO19152 LADM (Psomadaki, Dimopoulou, van Oosterom, 2016). It is a proposal for a comprehensive 3D multipurpose LAS supporting 2D and 3D cadastral registration in Greece.
This model is considered as an effort for overcoming current shortcomings, based on international standards, including the representation of a wide range of different types of spatial units in 3D, aiming to establish an appropriate basis for the National Spatial Data Infrastructure (NSDI) of Greece. Within the model, an attempt is made to cover all Greek land administration related information, which are currently maintained by different organizations.
This means that apart from the registrations of the Hellenic Cadastre (HC), other objects are also categorized and registered in the proposed model aiming at the creation of a multipurpose

land administration system for Greece. The different types of spatial units include areas with archaeological interest, buildings and unfinished constructions, utilities (legal spaces), 2D and 3D parcels, mines, planning zones, Special Real Property Objects (SRPO) usually found in Greek islands (anogia, yposkafa) and marine parcels. What makes the development of this model unique is the support of a wide range of spatial units, each of them having different requirements, several of them having a 3D aspect. The country profile also includes the content of various code lists, which are an important aspect of standardization.
According to ISO 19152, 2012, LA_Level and therefore, the Hellenic country profile specialization GR_Level is a collection of spatial units with a geometric or thematic coherence, an important concept for organizing the spatial units. For the proposed model, this structure allows for the flexible introduction of spatial data from different sources and accuracies, including utility networks, buildings and other 3D spatial units, such as mining claims, or construction works, etc. (see Figure 17).

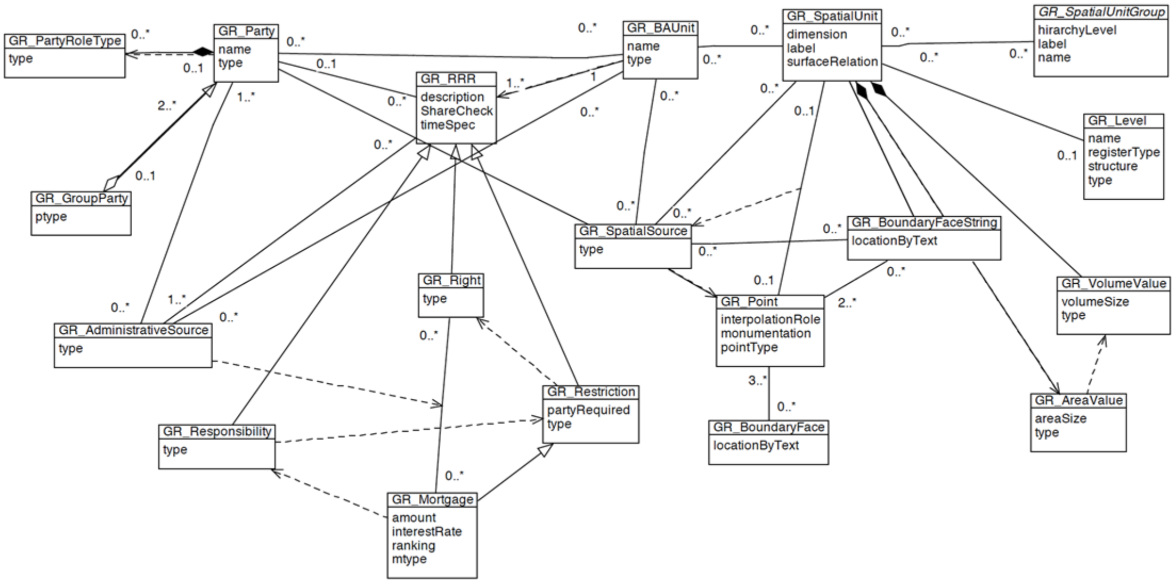

Figure 17. Proposed model graphically represented using UML INTERLIS Editor (Kalogianni E., 2016)

4.5 Poland

Góźdź and Pachelski (2014), Góźdź and van Oosterom (2015) introduced the 3D LADM based country profile, see Figure 18. They mention the fact that Polish cadastral system meets serious difficulty with providing information about the legal status of properties in case of 3D situations, when different property units are located above each other or even more complex structures, i.e. interlocking one another. For that reason, the presented Spatial Package is extended to new classes, e.g. PL_3DParcel.

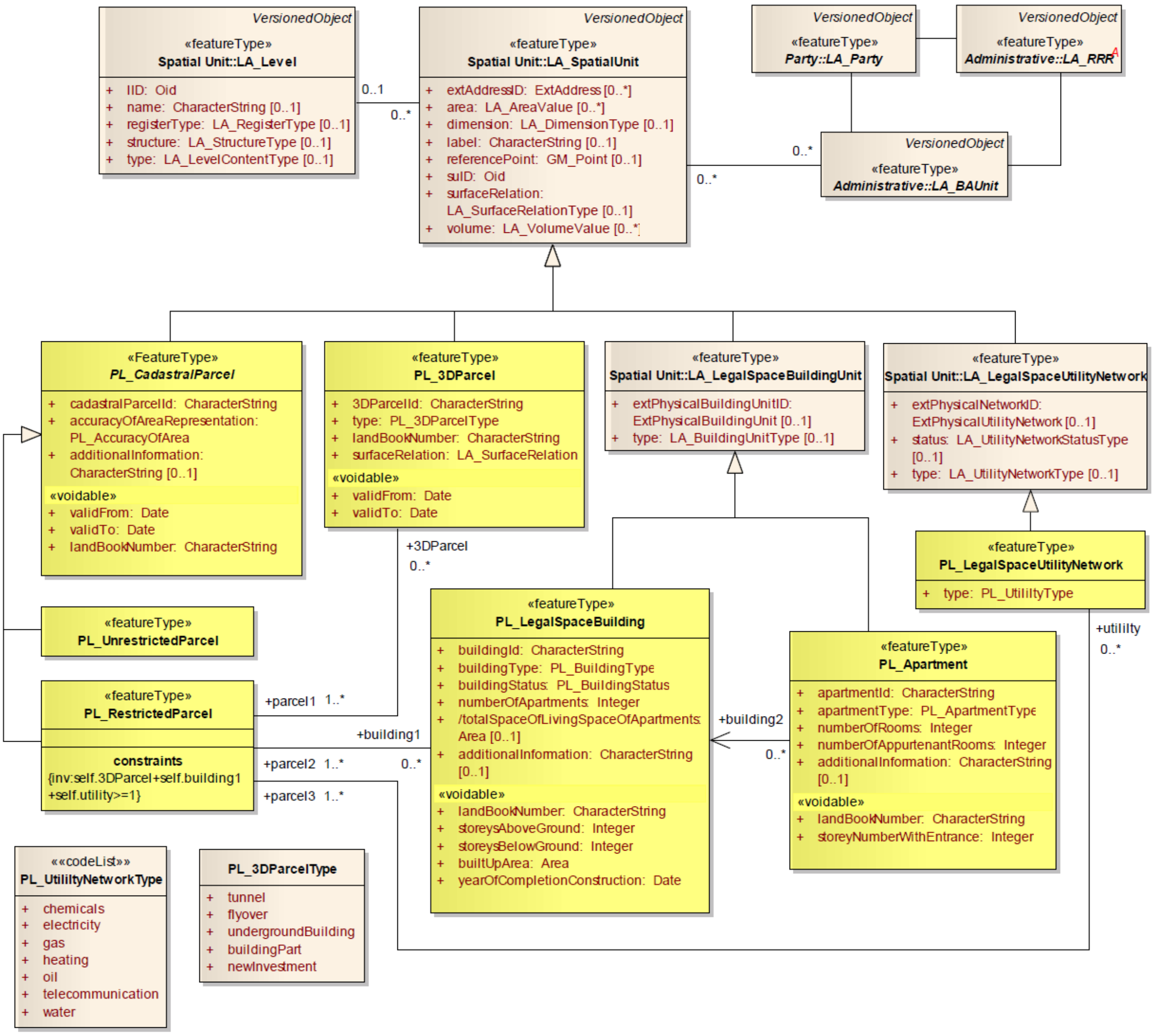

Figure 18. Spatial package of the Polish 3D LADM country profile (Góźdź and Pachelski, 2014)

5 CONCLUSION

In this concluding section, we revisited the various 3D Cadastral Information Modelling aspect, with focus on the gap between what is currently available and what is needed in an ideal situation. In the last subsection future work related to the upcoming revision of LADM is listed.

5.1 3D parcels

What are acceptable (valid) 3D cadastral object representationsn, and how to create their 3D geometries (even non-2-manifold geometries) are still challenges. The non-manifold 3D representations (self-touching in edge or node) are not well supported by current GIS, CAD, and DBMS software or by generic ISO standards such as ISO 19107 (van Oosterom, 2013). How to create and maintain valid 3D parcels is still a challenge in practice Ying et al. (2015). At least three aspects should be clearly developed in order to manage the 3D parcels correctly (Ying et al., 2015): (1) precise geometric models that describe the shapes and geographic locations of various 3D parcels based on flat faces; (2) volumetric or solid models that indicate boundary faces with orientation to present the corresponding 3D parcel objects; and (3) the topological relationships that encode the information about adjacencies between 3D parcels, using shared common faces/edges to preserve the consistency of the objects' geometries and support spatial query and management.

5.2 Interrelation CityGML – LADM ADE

An important trend which can be observed is the use of building information models/ construction plans to update the cadastral database, as done in Costa Rica (van Oosterom et al., 2014).

Further research will aim at investigating other possible alternatives of combining the LADM and CityGML standards (Góźdź et al., 2014) that is:

- embedding the selected CityGML classes into (broader) LADM framework,
- introducing a link between both domain models (in SDI setting) using references between object instances.

Unfortunately, it is not possible to indicate classes corresponding to LA_Party, LA_RRR and LA_BAUnit in CityGML, due to that fact there are many problems in the transformation of the model from conceptual to technical level. The results of this investigation suggest that introducing the semantic representation for land administration within CityGML will be advisable. That issue is included in the list of work packages that define the scope of next version of CityGML (Góźdź et al., 2014).

5.3 Ontology

For any developments that require spatial data, often the fusion of diverse spatial datasets is required. This becomes non-trivial when semantic heterogeneity occurs between schemas like CityGML and LandXML. Soon et al. (2014) introduced a semantics-based fusion framework to integrate CityGML and LandXML using the LADM OWL ontology previously developed. The LADM OWL ontology is augmented with the concepts of 'Physical Space Building Unit' and 'Physical Space Utility Network', which are related to 'Legal Space Building Unit' and 'Legal Space Utility Network' respectively through a new relation *hasLegalSpace*. Furthermore, they looked into how the extended LADM OWL ontology is linked with the CityGML schema and the Australian/Singaporean ePlan model (ICSM 2011) through the equivalent 'Class' relation. Syntactically, the equivalent 'Class' relation can be realized using the ExternalReference and DocFileRef elements of CityGML and LandXML respectively. The framework ultimately attempts to integrate not only the semantic models inherent in the schemas but also the geometries from CityGML and LandXML. Through this semantics based fusion, it is expected that a computer system will be able to do reasoning and inference in the OWL ontology. The computer system will also be able to retrieve the geometries of buildings' legal space or physical space, or both, through the ExternalReference and DocFileRef elements. The intention of the framework is to utilize the best of all worlds (i.e. CityGML, LandXML and OWL) without affecting the existing schemas, which have been comprehensively developed for different applications.

5.4 Open data and smart cities initiatives

One of the new areas is the creation of the 2D and 3D registries in the context of open data and smart cities initiatives that are aimed at providing a platform for city data. The inclusion of geospatial and building data in this context is paramount and was highlighted by the British Standard Institutions City Data Survey Report[9].

5.5 Compression and transfer of spatial data

3D models generally result in large data sets, which require special techniques for rapid visualisation and navigation (Breunig and Zlatanova, 2011). As the speed of geodata collection is still increasing, Janečka and Váša (2016) suggest that also the need for the effective geodata compression will be essential, for example to deliver the data to the final user/application via internet. They proposed a compression approach for geographical objects at various level of detail. For complex geographical objects, after the compression the amount of data is even lower than 4% of the original file size.

5.6 Future work related to the upcoming revision of LADM

Within ISO standards, which are actually being applied, are continued and subject to periodic revision, typically in a 6 year cycle. UN-GGIM Meeting of the Expert Group on Land Administration and Management was organized on 14-15 March 2017, Delft and the main conclusion was that indeed a LADM revision was needed in order to provide better tools to improve tenure security and better land and property rights for all. It was also noticed that it is a rather complex domain, with many stakeholders (ISO, FIG, OGC, UN-Habitat, UN-GGIM, World bank, GLTN (Global Land Tool Network), IHO, RICS,…). Further goals include: providing reliable LA Indicators for the Sustainable Development Goals (SDG), standard(s) supporting a Fit-for-Purpose approach, attention for implementations and tools (not just conceptual model), and inclusion of valuation information (which could might help to define/support Fit-for-Purpose approach). In order to prepare the LADM revision, a workshop was organized in 16-17 March 2017, with experts involved in the development of the initial version of LADM and representatives of all mentioned stakeholders. It is important to analyse and compare currently operational and proposed country profiles and their implementations of first version of LADM, ISO 19152:2012. The main, preliminary outcomes of the LADM 2017 workshop can be summarized as (van Oosterom 2017):

1. FIG makes New Work Item Proposal (NWIP) to ISO TC211
2. It is possible to start with an ISO Stage 0-project, given potential broad scope, including:
   - Fiscal/valuation extension module
   - More explicit semantics of code list values
   - Further modelling LADM’s rights, restrictions, responsibilities (RRRs)
   - Further modelling of LADM's survey and spatial representation
   - SDG Indicators (aggregated values at different levels)
   - 3D/4D Cadastre
   - Spatial planning/zoning with legal implications
   - LADM in support of Marine Cadastre (esp. coastal zones)
   - More explicit relations with Building Information Modelling (BIM)
   - Other legal spaces: mining, archaeology, utilities,…
3. Multi-part standard, 2-4 years development. Some initial thoughts:

[9] http://www.bsigroup.com/Documents/BSI_City Data Report_Singles FINAL.pdf *(accessed on 23 August 2016).*

- Part 0: Core (update current version LADM)
- Part 1: Potential conceptual model extensions
- Part 2: LADM Profiles (Methodology to define profiles, STDM, Sample country profiles)
- Part 3: Application schema, technical models & encodings (considering existing markup languages (xxxML): CityGML, IndoorGML, InfraLand (InfraGML), LandXML, Own/new land administration markup languages → LAML, (Geo)BIM/IFC, INTERLIS, Linked data (RDF), GeoJSON,…)
- Part 4: Process & workflow standardization
- Sample implementation

4. OGC Innovation Program (with the option that National Mapping and Cadastral Agencies (NMCA) support developed countries)
5. GLTN support for developing countries
6. In collaboration with many partners (more than list below)

The list above shows that the revision could have rather a wide scope and result in a complex process. The intention is that the next steps will be made during the 7th FIG Workshop on the Land Administration Domain Model, Zagreb, Croatia, 12-13 April 2018 (see http://isoladm.org).

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Chapter 4. 3D Spatial DBMS for 3D Cadastres

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Key words: 3D Spatial Database Management System, 3D Cadastre, 3D Representation, 3D Spatial Indexing and Analysis

SUMMARY

Subdivision of land parcels in the vertical space has made it necessary for cadastral jurisdictions to manage cadastral objects both in 2D as well as 3D. Modern sensor and hardware capabilities for capture and utilisation of large point clouds is one of the major drivers to consider Spatial Database Management Systems (SDBMS) in 3D and organisations are still progressing towards it. 3D data models and their topological relationships are two of the important parts of 3D spatial data management. 3D spatial systems should enable data models that handle a large variety of 3D objects, perform automated data quality checks, search and analysis, rapid data dissemination, 3D rendering and visualisation with close linkages to standards. This chapter asserts that while there has been work done in defining 2D and 3D vector geometry in standards, it is still not sufficient for 3D cadastre purposes as 3D cadastral objects have a much more rigorous definition. The Land Administration Domain Model (LADM), which is an ISO Standard, addresses many of the issues in 3D representation and storage of 3D data in a database management system (DBMS). The chapter further discusses the various approaches to storing 3D data such as through voxels, or point cloud data type and elaborates on the characteristics of a 3D DBMS capable of storing 3D data. Approaches for spatial indexing to improve the fast access of data and the various available options for a 3D geographical database system are presented. Several spatial operations on and amongst 3D objects are illustrated with linkages to the current standards including the LADM. Next, construction of 3D topological and geometrical models based on standards and including their characteristics is discussed. Current 3D spatial database managements systems and their characteristics, including some comparison between selected DBMS including the hardware capabilities are elaborated in detail. Finally, the chapter proposes a 3D topology model based on Tetrahedron Network (TEN) synchronised with LADM specifications for 3D cadastral registration. This topological model utilises surveying boundaries to generate 3D cadastral objects with consistent topology and rapid query and management capabilities. The definition for validation of 3D solids also considers the automatic repair of invalid solids. Point cloud and TEN related data structures available in SDBMSs are also investigated to enable storage of non-spatial attributes so that database updates would store all spatial and attribute information directly inside the spatial database.

1. INTRODUCTION

With the advancements in computing and spatial science based technologies, the generation and usage of 3D data is now possible with much ease than before.
Boss and Streilein (2014) observed four major technology and business drivers for 3D:

1. There are massive new sensor hardware capabilities, such as automated data capture and model creation on the sensor side, LIDAR with masses of point clouds and automated photogrammetric workflows and processes.
2. 3D visualisation has now come into the mainstream, but 3D analysis has not. But there is as yet no mass market with consumer-focused systems.
3. Managing 3D data in enterprise workflows with improved performance and scalability of existing workflows and bridging the gap between point cloud surveys, GIS, CAD, BIM. Traditional file handling moves to database management.
4. There is a necessity for 3D data, where 2D data is not sufficient to describe our world and the consumer expectation demands three dimensions, as we all live and act in a three dimensional environment.

For cadastral organizations, who traditionally describe their cadastral data in two dimensions and hold their information in 2D (often graphical) files, concepts for entering the third dimensions are not yet available, mainly due to the facts that (Boss and Streilein, 2014):

- 3D modelling is much more heterogeneous and complex compared to 2D modelling,
- Converting 2D data to 3D data on an operational level, with not just adding a Z-coordinate onto each planimetric pair of coordinates, is quite cumbersome and there is no 'best' solution obvious, as the existing datasets are usually quite specific,
- One has to migrate from simple data structures to complex data structures,
- One has to deal with the economic and sustainability issues of handling and storing high data volumes compared to (relatively) low data volumes in the current years, and
- User-friendly tools for 3D analysis are still missing.

The technologies for creating and using 3D models have matured over the past ten years. People are accustomed to use 3D technologies in their daily life, ranging from watching TV and movies in 3D, gaming and 3D printing to navigating through 3D maps. Still 3D technologies are not common to solve location-based issues: spatial planning is still mainly done based on 2D maps and databases with geo-information that support location-related policies (like INSPIRE, building registers, land use plans, cadastral maps) are mainly 2D (Stoter et al., 2016).
In our contemporary social context, the development of land use has subdivided land parcels into three-dimensional (3D) spaces according to certain property rights, especially in metropolitan areas with dense population. This results in 3D parcels (ISO, 2012) above or below the land surface. In such circumstances, the local government needs to construct and manage 3D cadastral objects to be able to manage the development of real urban 3D spaces appropriately (Ying et al., 2015).
Constructing 3D data models and their topological relationship are two important parts of 3D cadastre (Ying et al., 2011). 3D Spatial Systems should then enable (Ravada et al., 2009):

- Data Model to handle a variety of 3D Objects
- Data quality control
- Geo-Referencing

- Comprehensive Location based search and Analysis
- Handling level of detail for seamless operation
- High Performance dissemination of 3D data
- Support High performance real-time 3D rendering
- Support for 3D Standards

This chapter addresses several topics: the different types of 3D spatial representations (vector, voxel and point cloud) (Section 2), 3D spatial indexing and clustering (Section 3), 3D geometries and 3D operations (Section 4), 3D topology structures (Section 5), from theory to practice (Section 6), recent development of spatial databases (Section 7), analysis, what is available and what is needed (Section 8). The chapter ends with conclusions.

2. 3D SPATIAL REPRESENTATION

2.1 Vector representation

Practically most of the work on geometry models has been completed by the Open Geospatial Consortium Inc. (OGC, formerly the Open GIS Consortium) (Lee and Zlatanova, 2008). ISO has also independently from OGC developed ISO/TC 211 19107:2003 (ISO, 2003), Geographic information – Spatial Schema (Hering, 2001).

The OGC Implementation Standard for Geographic information – Simple feature access – Part 1: Common architecture (OGC, 2011) describes the common architecture for simple feature geometry. The simple feature geometry object model is Distributed Computing Platform neutral and uses unified modelling language (UML) notations. The base Geometry class has subclasses for Point, Curve, Surface and GeometryCollection. Each geometric object is associated with a Spatial Reference System, which describes the coordinate space in which the geometric object is defined. This part of OGC Simple feature access implements a profile of the spatial schema described in ISO 19107:2003, Geographic information – Spatial schema.

The OGC Implementation Standard for Geographic information – Simple feature access – Part 2: SQL option (OGC, 2010) defines a standard Structured Query Language (SQL) scheme that supports storage, retrieval, query and update of feature collections via the SQL Call-Level Interface (SQL/CLI). A feature has both spatial and non-spatial attributes. Spatial attributes are geometry valued, and simple features are based on two-or-fewer dimensional geometric (point, curve and surface) entities in 2 or 3 spatial dimensions with linear or planar interpolation between vertices.

Kazar et al. (2008) and Verbree and Si (2008) observe that the ISO 19107 solids are not sufficient for 3D cadastral applications: the ISO 19107 solid is a simple solid whose shell is not allowed to touch (it needs to be a 2-manifold).

For proper representation of 3D cadastre, adequate 3D geometries are required. Surveying data can be acquired by the surveyors or the engineers, thus the creation and submission of 3D volumetric objects are the key phases in a 3D cadastre system. However, what are acceptable (valid) 3D cadastral object representations and how to create their 3D geometries (even the non-2-manifold geometries) are still challenges (van Oosterom 2013). The non-manifold 3D representations (self-touching in edge or node; see Figure 1) are not well supported by current GIS, CAD, and DBMS software or by generic ISO standards such as ISO 19107 (van Oosterom 2013).

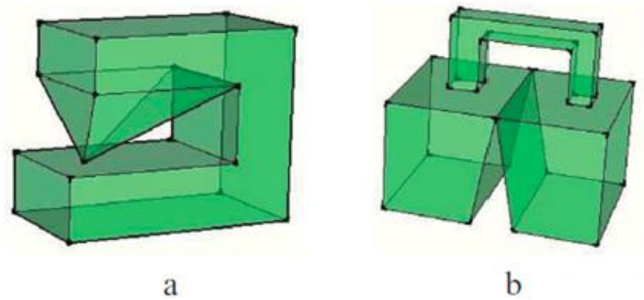

Figure 1. Solids with non-manifold conditions: (a) point non-manifold condition; and (b) edge non-manifold condition (Ying et al., 2015)

Kazar et al. (2008) and Thompson and van Oosterom (2012) give the definition of a 3D parcel for 3D cadastre purposes. The main rule is that the volumetric object is internally connected, which means that a shell can self-touch, as long as the interior of the solid stays connected. Ying et al. (2015) follow this definition and state that a valid volumetric object is a 3D primitive that can be represented by one close polyhedron, refined by a set of connected faces. The volumetric object satisfies the following characteristics: closeness, interior connection, face-construction and proper orientation. Evidently, the volumetric object here can have through-hole/ring or cavity that allows its boundary faces to touch each other, which is not a 3-manifold in some cases.

2.1.1 Considering Land Administration Domain Model (LADM) standard

The LADM international standard ISO 19152 (ISO, 2012) represents parties (natural and non-natural persons), spatial units (survey and geometrical/ topological representations) and their relationships through rights, restrictions and responsibilities (RRRs). In this standard, the RRR, applying on a given spatial unit, or a group of spatial units, are defined in a bundle form using a basic administrative unit applied to a given spatial unit, or a group of spatial units.
Figure 2 shows a simplified database storage scheme proposed by Thompson et al. (2016) able to represent the various types of spatial units. Compared to ISO 19152, the classes LA_SpatialUnit and LA_BoundaryFaceString have been combined into a single class (LA_SpatialUnit) as there is in this context a 1-to-1 relationship between the two classes which is still conformant with ISO 19152.
There are two reasons why a polyhedron attribute of type GM_Solid for 3D spatial units is not appropriate: 1. in most cases there is an overlap between the vertical faces of polyhedron and the LA_BoundaryFaceString defined by the footprint (redundant and possible cause of inconsistency), and 2. the GM_Solid can only represent fully bound spaces. Therefore, this is not a suitable solution and the association with LA_BoundaryFace is used instead.

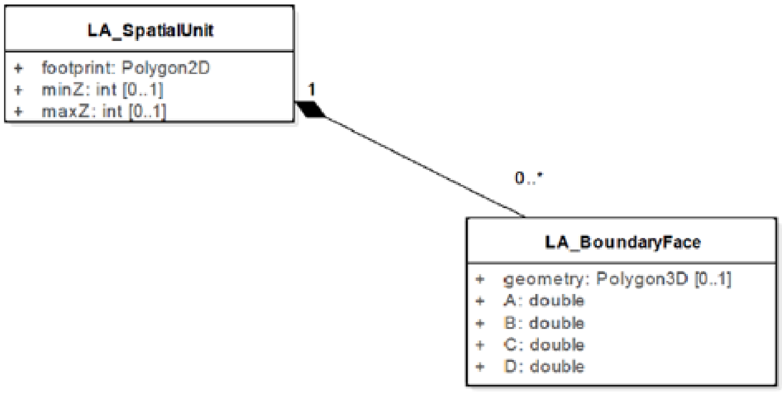

Figure 2. Simplified schema for database storage (Thompson et al., 2016)

Also note that in the simplified scheme, there is no sharing of LA_BoundaryFace's among different LA_SpatialUnit's and the association between LA_SpatialUnit and LA_BoundaryFace is also not signed (indication + or – orientation of face when used in a 3D LA_SpatialUnit). This is possible in ISO 19152 and also fits quite well in the proposed style of LandXML transport encoding - Nested Parcels Method (Thompson et al., 2016).
In a DBMS that allows in-row storage of simple geometries, this form is highly efficient. For example in PostgreSQL/PostGIS or Oracle Spatial, simple 2D spatial units (such as four sided city blocks) will be stored in-row, permitting very fast retrieval. In addition, access can be in one of three forms: 1: as a 2D footprint (this could be compared to LoD0 (level of detail) in CityGML); 2: as a "Prism" (footprint with top and/or bottom, this could be compared to LoD1 in CityGML); 3: as a complete 3D geometry (the higher LoD's in CityGML, including indoor, as one building may contain multiple spatial units) (Thompson et al., 2016).
Thompson et al. (2016) further elaborate that the down-side of this model is that there is duplication of the definition of boundaries that separate spatial units (one copy for each spatial unit involved), leading to the potential for incompatible definitions of the same boundary. The broad approach in terms of a storage scheme is that a more-or-less conventional 2D complete, non-overlapping topological coverage of the region of interest would be generated (sharing 2D boundaries), while 3D surfaces would be shared by and would separate spatial units that are adjacent in 3D, but overlapping in 2D. A secondary advantage of this approach is that it effectively supports liminal parcels as defined in the LADM (ISO, 2012).
Another issue is that if a footprint is stored as a polygon, most DBMSs do not permit any attributes to be recorded on the individual lines - such as the nature of the line. This is an area needing consideration and in principle the LADM supports management attributes on the boundary level: both for lines (LA_BoundaryFaceString) and faces (LA_BoundaryFace) (Thompson et al., 2016).

2.2 Voxel representation

Voxel, a volumetric pixel, is a quantum unit of volume and has a numeric value (or values) associated with it that represents properties or independent variables of a real object or a value from a continuous field. Representing 3D urban scenes by voxels bring a number of advantages: calculating volumes is a matter of counting the number of voxels that constitute an object, 3D bisections become simple selection operations, storing volumetric spaces such as air, water, and underground is possible. An additional benefit of voxel storage is the atomicity of

the data type; every object is represented by only one primitive (3D cube) instead of the surface representation (i.e. points, lines and polygons) (Zlatanova et al., 2016)).
Voxel storage offers a number of interesting simplification, use cases, as well as challenges. One of the major challenges is its storage and efficient handling by spatial database management systems (Gonçalves et al., 2016).
It is clear that a dense flat relational table is not ideal storage format for a large 3D grid. The Holy Grail is an architecture which allows effective compression to reduce storage footprint, and efficient data retrieval to access only the attributes of interest at a specific resolution. Such key features is what distinguishes a column-oriented architecture from a record-oriented architecture and the reason for their efficiency on analytical workloads (Abadi et al., 2008).
Despite column-oriented architectures emerging as the right candidate, their flat storage model is not yet suitable to store a large 3D city model. Gonçalves et al. (2016) extended a column-store to also support a nested column-oriented storage for 3D city models. The chosen format is Parquet[1]. It is an effective storage model for sparse data sets with a nested structure (the different LODs). Its flat columnar format fits well with the column-oriented programming model. Parquet file layout is represented in Figure 3.

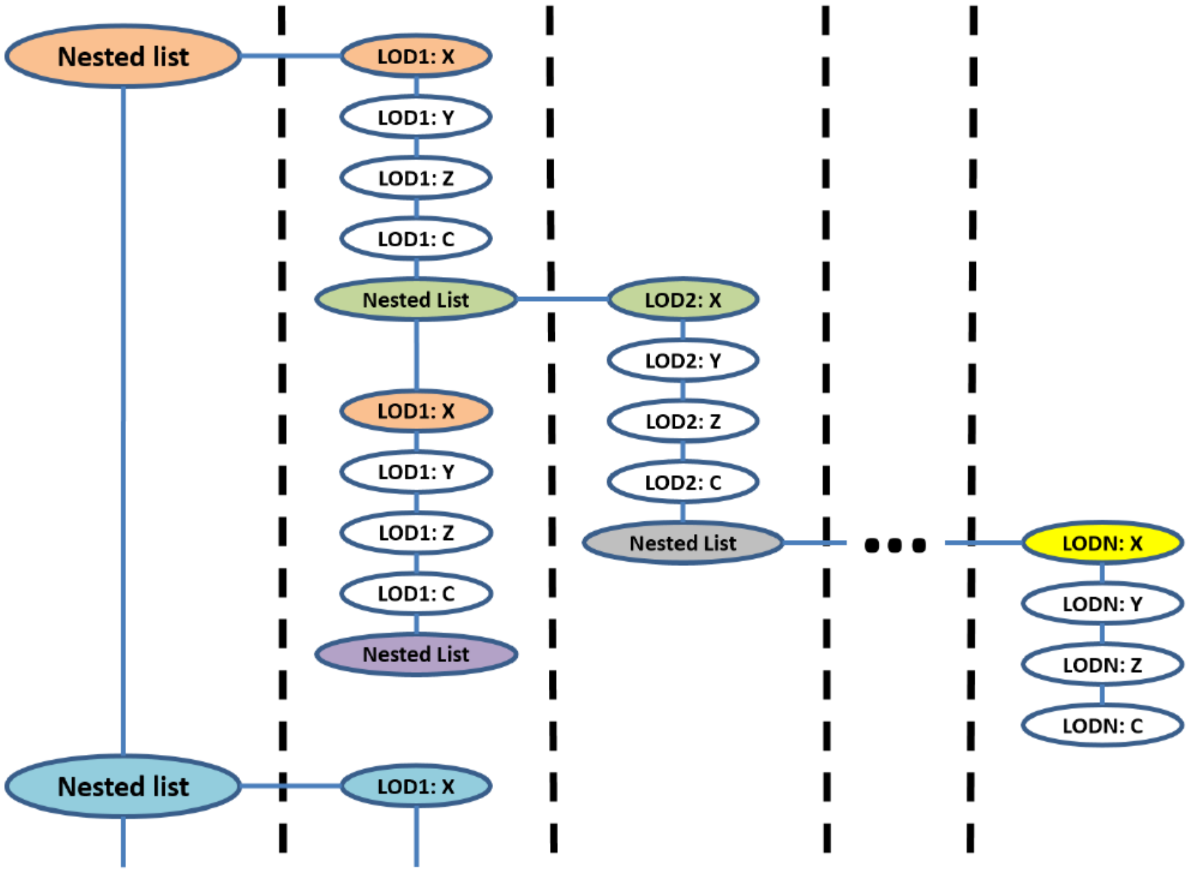

Figure 3. Parquet file layout (Gonçalves et al., 2016)

[1]http://parquet.apache.org/ *(accessed on 21 August 2016)*

Storage challenges

For the storage and indexing of 3D voxels linked with properties, such as voxels created to simplify a point cloud, two approaches can be considered, a homogeneous voxel grid versus a heterogeneous voxel collection. The former allows for factorization of invariant properties from the data structures, while the latter is better suited to sparse models such as a 3D city model with different LODs. A homogeneous voxel grid is easy to define using a flat relational schema, i.e., real-world objects are formed by semantically grouping voxels together via foreign key relations and relational views. The schema normalization is used to reduce the storage footprint at the cost of expensive spatial joins. The schema normalization storage footprint is proportional to the size of each voxel. Hence, efficient data access becomes dependent on efficient column compression techniques and effective storage of geometric empty spaces. A heterogeneous voxel grid poses extra challenges compared to a homogeneous voxel grid due to the preservation of the geometry semantics when converting vector to raster data. The object’s semantics depends on the semantic level of detail (LOD) (Gonçalves et al., 2016).

Nested column-oriented storage

For efficient storage and data retrieval at different resolutions, Gonçalves et al. (2016) embraced a column-oriented format for voxel-based 3D city models. Columnar formats have several advantages. Organization by column allows better compression, as data is more homogeneous. For large data sets the I/O is improved since it is possible to efficiently scan a subset of the columns while reading the data. Hence, to store nested data structures in flat columnar format, the schema is mapped to a list of columns in such a way that records are written and read back to its original nested data structure in an efficient way.

3D raster spatial DBMS

A voxel-based 3D city model is best managed in a spatial DBMS as each voxel has a semantic relation to a real world object and various attributes (for example color, material, porosity, reflection properties, etc.). Furthermore, a single spatial DBMS offers all functionality in one place, avoids the need for multiple software tools with associated high volume data transfer and format transformations (Gonçalves et al., 2016). They also assert that Oracle Spatial, Graphs 12c, and PostgreSQL 9.2 are developing extensions to support 3D geometries. In GIS packages, only GRASS has support for voxels, but it still stores them as flat files. The systems are still in their infancy and they offer limited functionality. Due to the complexity of their software stack, deep integration with the database engine is even further away. For their work they have extended a modern column-store, MonetDB (Idreos et al., 2012), which steps away from traditional SDBMS which are all record-oriented architectures. Through vertical partitioning of relational tables column-store significantly reduce data access. MonetDB spatial features have been matured to provide core technology components for geo-spatial big data analytics. Atomic spatial types and their operations are becoming part of the relational kernel and not an add-on. All the operations are available for spatial applications through integrated environments, such as R and Python, and a SQL front-end.

The recent development in the field of nD-array databases is described in more detail in section 7.1 nD-array Database Management Systems.

2.3 Point Cloud Database Management Systems

2.3.1 Considering LADM standard

There are two main situations in which point cloud data (see Figure 4) are of importance: one as 3D reference and two as input for the creation of 3D parcels.
The first use of point clouds in the context of 3D Cadastre, is related to the visualization of 3D parcels, were we often use reference information in order to understand the location and extent of 3D parcels. Also in the case of 2D often reference information, such as buildings, road, and waterways, are used in combination with the parcels of the cadastral map. Both in 2D and in 3D this reference information is usually in the form of vector models; for example in 3D this is BIM/IFC or CityGML. However, in 3D also point clouds could be used for this. Not only to show reference objects (building, roads), but also to give an indication of the Earth surface. It is very important to know if a 3D parcel is below, on, above the Earth surface or maybe even a mixed configuration. The benefits of using point clouds is that they are close to data acquisition, quite detailed and realistic, and do not require the often costly operations needed for the interpretation, classification and conversion to vector representation.

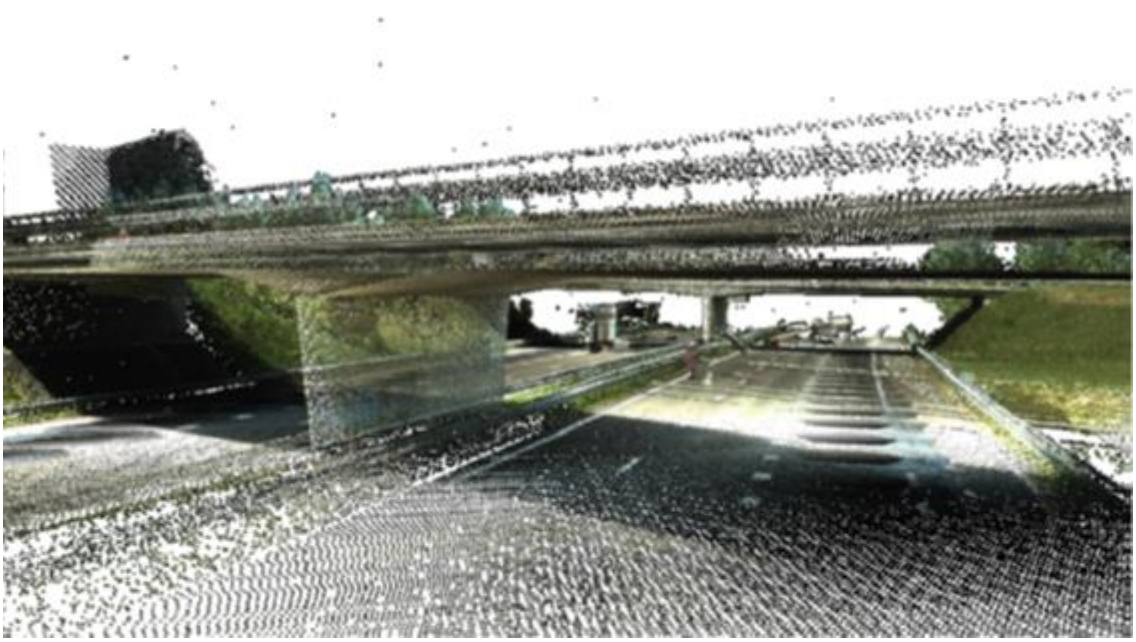

Figure 4. Example point cloud, related to a 3D construction

The second use of point clouds in the context of 3D Cadastre, is related to the creation of 3D parcels (see chapter Initial registration). 3D plans of 3D parcels, to be generated in the form of the physical objects with Rights, Restrictions and Responsibilities (RRR's), could be used when creating the 3D parcels, that is, legal spaces related to real world objects. A point cloud could be used to check if the construction is indeed realized as indicated on the plan (and therefore the local of the legal spaces is also correct). However, in case of older constructions these 3D plans may not be available at all, and in these situations collecting reference information in the form of a point cloud may be very effective.

2.3.2 Nature of the point cloud data

State of the art spatio-temporal representations are based on either gridded (raster, voxel) or object (vector) models. Point clouds are in between: they share with the gridded model the sampling nature, and they share with the object model the ability to represent arbitrary locations (points). Today both vector models and gridded (in 3D voxel) models are quite well supported in spatial DBMSs and other software tools. After realizing the importance of the point cloud representation, there is now also an increase in support for managing the point clouds also within the spatial DBMS.

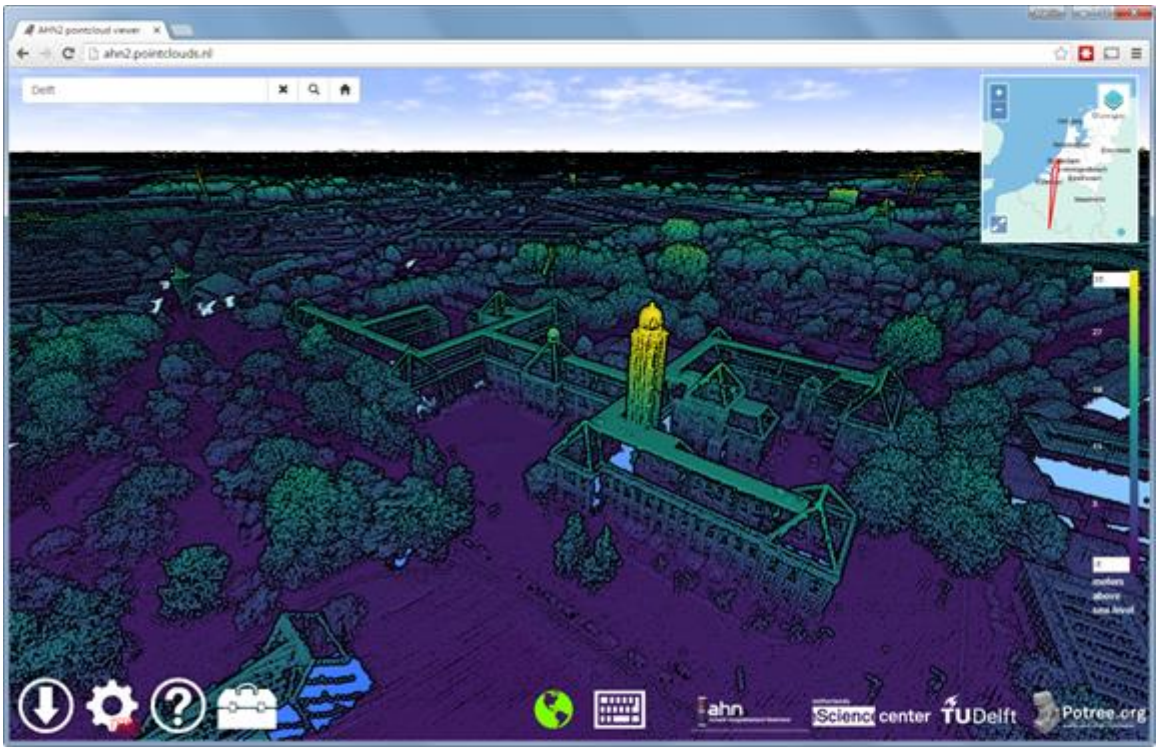

Figure 5. Point cloud data in a 3D web viewer (ahn2.pointclouds.nl)

There are various sources of indoor and outdoor point clouds, but it is fair to state that one common characteristic is they all produce rather large volumes of data. Lidar, photogrammetry, and various other survey technologies enable the collection of massive point clouds. Faced with hundreds of billions or trillions of points the traditional solutions for handling point clouds usually underperform even for classical loading and retrieving operations. To obtain insight in the features affecting performance, in earlier work (van Oosterom et al., 2015, van Oosterom et al, 2016) tests were carried out with different storage models on various systems, including Oracle Spatial and Graph, PostgreSQL-PostGIS, MonetDB and a file based solution: LAStools by Rapidlasso GmbH 2015. It should be noted that web services based on point cloud data are becoming more popular, and these could also be used very well in the context of 3D Cadastre. The requirements that these 3D web viewers pose, including level-of-detail (perspective) selections (see Figure 5), are rather difficult to meet given the huge volumes of data.
The users have a range of different datasets and types: administrative data, vector data, raster data, temporal data, etc. Therefore, a standardized and generic DBMS solution would be preferable above file based solutions when users want to combine data. Therefore, it is proposed to add a third type of spatial representation to the geographic information processing systems

and standards: a point cloud data type. Based on user requirements the point cloud data type and its operators should cover (van Oosterom et al., 2015):

1. XYZ: specify the basic storage of the coordinates in a spatial reference system (SRS) using various base data types: integer, float, double, number, varchar.
2. Attributes per point: 0 or more. Example attributes are intensity I, colour RGB, classification, observation point position in addition to resulting target point, etc.
3. Data organization based on spatial coherence: blocking scheme in 2D, 3D, etc.
4. Efficient storage with compression techniques exploiting the spatial cohesion.
5. Data pyramid support: level of detail (LoD), multi-scale or vario-scale and support for perspective selections.
6. Temporal aspect: options for time per point (costly) or per block (less refined).
7. Query accuracy: for 2D, 3D or nD query ranges or geometries specify to report points or storage blocks and refine subsets of blocks with/without tolerance value.
8. Operations/ functionalities in the following categories: (a) loading, (b) selections, (c) simple analysis (not assuming 2D surfaces in 3D space), (d) conversions (some assuming 2D surfaces in 3D space), (e) towards reconstruction, (f) complex analysis (some assuming 2D surfaces in 3D space), (g) LoD use/access, and (h) updates.
9. Indicate the use of parallel processing for the operations listed in the Point 8.

2.3.3 Point Cloud Management Systems

The suitability of Database Management Systems (DBMS) for managing point cloud data is a continuous debate. File-based solutions provide efficient access to data in its original format, however, data isolation, data redundancy, and application dependency on such data format are some major drawbacks. Furthermore, file-based solutions have also poor vertical and horizontal scalability. In comparing both DBMS and File-based solutions for point clouds two storage models can be identified:

- Blocks model: nearby points are grouped in blocks which are stored in a database table, one row per block
- Flat table model: points are directly stored in a database table, one row per point, resulting in tables with many rows.

The DBMS with native point cloud support based on the blocks model are Oracle Spatial and Graph and PostgreSQL-PostGIS. For more information regarding the various point cloud storage models and their tuning (block size, compression), please refer to an earlier publication (van Oosterom et al. 2015). In addition to using native blocks solutions, it is also possible to use third-party block solutions. Point Data Abstraction Library (PDAL) is a translation library for manipulating point cloud data and it is used, in general, as an abstraction layer on management operations. Thus the same operations are available independently on which system (DBMS or File-based) actually contains the data.

3. 3D SPATIAL INDEXING AND CLUSTERING

The important aspect of 3D data management is spatial indexing. Spatial indexes are used in DBMS for fast search especially when spatial functions are applied. Without indexing, any searches for a feature would require a sequential scan of every record in the database. Indexing speeds up searching by organizing the data into a search tree that could be quickly traversed to find a particular record.

The review of spatial indexing is given in Breunig and Zlatanova (2011). Within the current Spatial Database Management Systems, for example PostGIS and Oracle Spatial, there are several types of indexes (Khuan et al., 2008): they are B-Tree indexes, R-Tree indexes (Guttman, 1984), and GiST indexes.

- B-Trees are used for data, which can be sorted along one axis; for example, numbers, letters, dates. GIS data cannot be rationally sorted along one axis (it is difficult to determine which is greater, (0,0) or (0,1) or (1,0)) so B-Tree indexing is of limited use for the GIS user.
- R-Trees break up data into rectangles, and sub-rectangles, and sub-sub rectangles, etc. R-Trees are used by some spatial databases to index GIS data, for example Oracle Spatial implements the 2D and 3D R-Trees.
- GiST (Generalized Search Trees) indexes break up data into 'things to one side', 'things which overlap', 'things which are inside' and can be used on a wide range of data-types, including GIS data. PostGIS uses the R-Tree index implemented on top of GiST to index GIS data.

Several strategies have been developed for indexing of multidimensional data, although there is limited vendor support for these, and true 3D index creation is still an ongoing research problem (Schön et al., 2009).

3D R-tree

This section is based on the article of Zhu et al. (2007). R-tree is considered as one of the most promising 3D spatial indices. In an ideal case, the neighbouring objects should be in the same nodes or sibling nodes, the minimum bounding rectangle (MBR) of sibling nodes is different, and the overlap is then minimized. However, when the index expands from 2D to 3D, because of the great size and shape diversity of different objects in 3D space, the minimum bounding box (MBB) of sibling nodes will frequently overlap, and the MBBs of nodes can even contain each other. The better space proximity of R-tree is therefore the key to 3D spatial indexing in order to adequately take into consideration the principle of 3D spatial proximity. 3D spatial clustering and the corresponding 3D R-tree indices are required in order to minimize the overlap among the sibling nodes and to balance the shape and size of nodes. Proximal objects cluster together in 3D space in the same nodes or proximal sibling nodes.

For dynamic indexing as well as R-tree construction, both insertion and deletion are important basic operations. The insertion operation is more critical to the R-tree construction procedure in complicated 3D space. The insertion of an object would result in the splitting of the R-tree node, and cluster grouping is usually used to support node splitting and node optimization.

Zhu et al. (2007) propose a 3D R-tree algorithm based on 3D spatial cluster grouping. They first propose an integrative grouping criterion *W* concerned with the 3D overlap, 3D coverage and MBB shape value of nodes. Then the *k*-means algorithm is employed to improve the 3D spatial cluster grouping and inserting operation of 3D R-tree.

3D integrative grouping criterion

For a 3D spatial object set $S = \{P_1, P_2, \ldots, P_n\}$, there are clustered group sets S_i, $i = 1, \ldots, k$ and the integrative grouping criterion value W can be calculated using the equation:

$$W = \sum_{i=}^{k-1} \sum_{j=i+1}^{k} \text{Overlap}(S_i, S_j) + \sum_{i=1}^{k} \text{Coverage}(S_i) + \sum_{i=1}^{k} \text{Shape}(S_i).$$

The smaller the *W* value, the better the 3D spatial cluster grouping results.

3D spatial cluster grouping

The 3D spatial cluster grouping operation includes two steps: the node splitting and the optimization among nodes. Figure 6 illustrates a typical grouping result. As shown in Figure 6, the wire frame box denotes the node that needs to be split, and solid boxes denote the child nodes, and in this example it is obvious that splitting the child nodes into three groups is more rational than into two groups. For this purpose, a new 3D spatial-cluster grouping algorithm is introduced, in which the k-means clustering method of data mining is employed to partition k clusters in a set concerning the 3D spatial layout of objects. As both the spatial coverage and overlap of nodes should be minimized, as well as the shape of MBB nodes being considered, the above mentioned integrative grouping criterion value W is used as the grouping criterion.

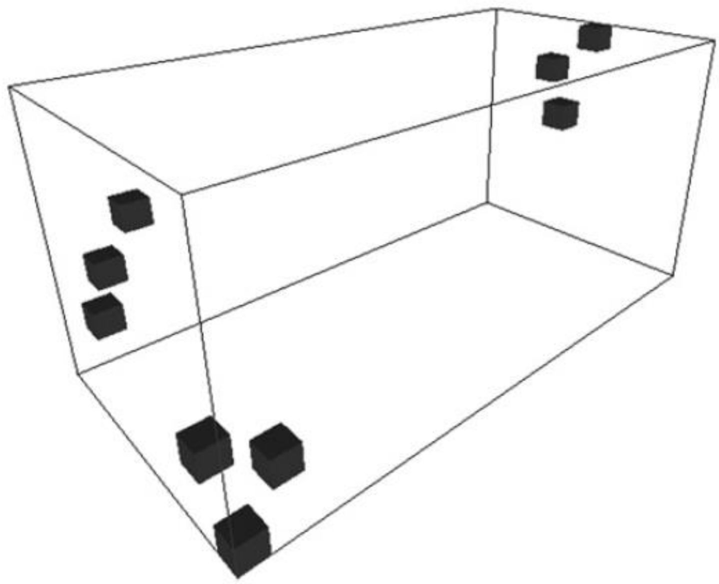

Figure 6. Spatial cluster grouping (Zhu et al., 2007)

Figure7 illustrates the flow chart of the 3D spatial cluster grouping algorithm, which includes spatial clustering and spatial grouping.

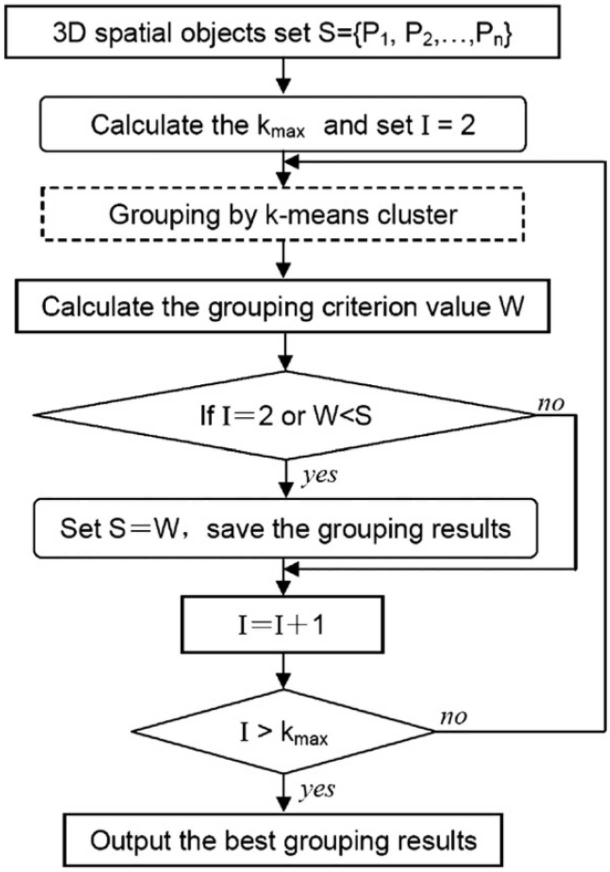

Figure 7. Flowchart of the 3D spatial cluster grouping algorithm (Zhu et al., 2007)

Spatial clustering

Step 1: Calculate the maximal group numbers k_{max}. Ensure that $n/k_{max} \geq m$, where n is the number of total spatial objects, m is the minimal number of children in a node.

Step 2: Choose different group numbers I (I = 2, …, k_{max}) as parameters; adopt the spatial grouping algorithm given below to calculate the corresponding integrative grouping criterion value W using equation above. Select the grouping strategy with the minumum value of W as the final grouping result.

Spatial grouping

Input: 3D spatial object set $S = \{P_1, P_2, ..., P_n\}$.

Output: k small group sets with inserted objects S_i, i = 1, …, k.

The details about the spatial grouping algorithm (and also 3D R-tree insertion) give Zhu et al. (2007).

Figure 8 illustrates an experimental result of 3D R-tree generation. The R-tree possesses inherent inefficiencies when applied to LiDAR data (Schön et al., 2013). They proposed an octree index for 3D LiDAR data atop Oracle Spatial 11g.

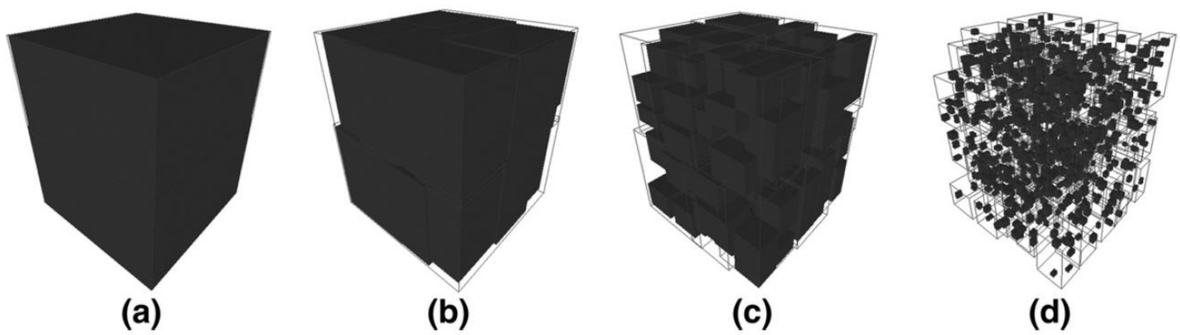

Figure 8. 3D R-Tree generation procedure. (a) Root layer. (b) 2nd middle layer. (c) 3rd middle layer. (d) Leaf layer (Zhu et al., 2007)

Octree

An octree's structure dictates that each internal node contains exactly eight child nodes regardless of its many variants. In the implementation herein a bucket point region (PR)-octree approach was adopted, where the space is decomposed into cubic blocks (or cells) through recursion, until a block is homogeneous.

By definition, an octree can result in an unbalanced hierarchical tree when the data distribution is not uniform. However, this requires the storage of the logical tree structure in the SDBMS for recursive reconstruction of the tree structure during query processing.

Therefore, the proposed implementation employs a fixed, maximum tree height (also called its tiling level), thereby resulting in a balanced tree. This improves query efficiency as neither the tree structure nor recursive cells need to be stored, only the tiling level. The selection of an appropriate tiling level is a decisive factor, involving the dataset's area and size. As such, experimentation with different levels is needed to optimize performance for a specific dataset.

The user can specify the tiling level through the parameter OCTREE_LEVEL during index creation. Each cell is associated with a unique code, here in referred to as the cell code. The cell code is obtained by using z-ordering of all cells at the specified level.

Figure 10 illustrates the 3D space decomposition through an octree, and Figure 9 illustrates cell code generation. All cells in the bottom half are assigned with the prefix '0'—zero, and all in the top half are assigned with prefix '1'—one. Cells are marked south-west (SW), south-east (SE), north-east (NE) and north-west (NW) and associated codes are 00, 01, 10, and 11 consecutively. The associated cell code is identified by traversing the octree from root node to leaf node. For example, using B to represent the bottom half and T to designate the top half, at tiling level 5, the code for the path BNW(011)–TSW(100)–TNE(110)–BSE(001)– BSW(000) is 011100110001000. Here, it only follows the tree path where the cell associated to a node in the path contains the point. The point's ROWID and associated cell code are stored in an index storage table. The metadata (for example, tilinglevel, indexname, index owner, max level, min level, etc.) for the entire index are stored as a row in an table called index metadata table (Schön et al., 2013).

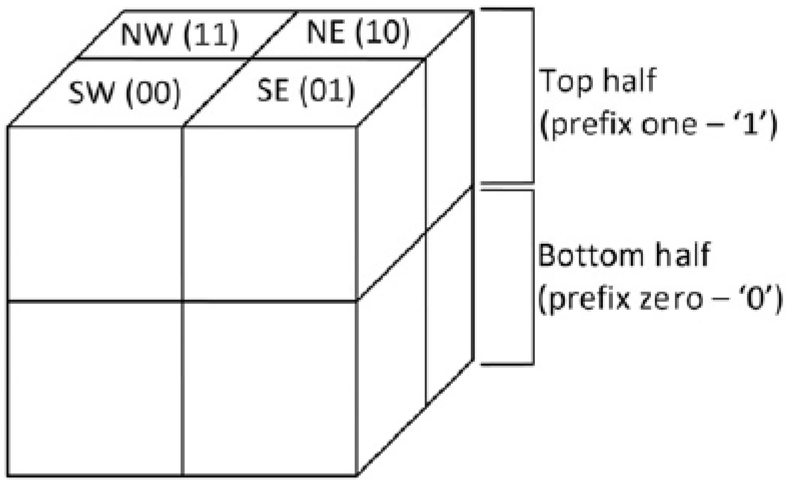

Figure 9. Quadtree sectors (Schön et al., 2013)

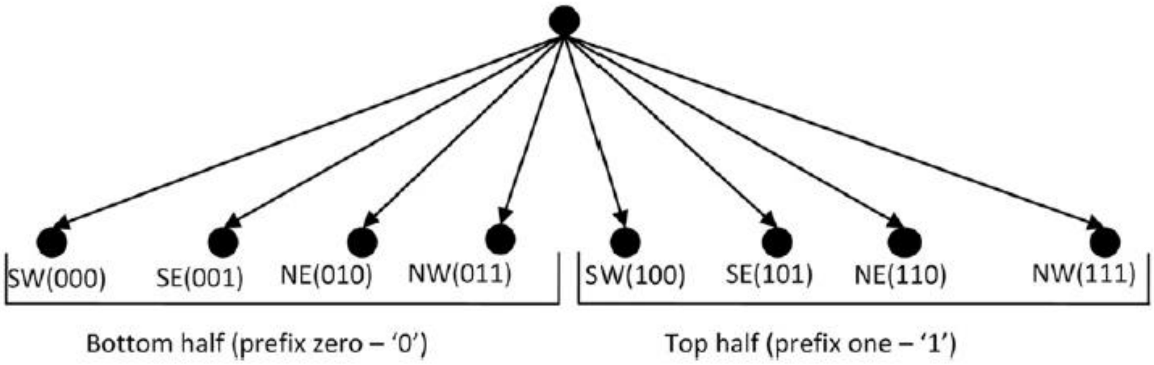

Figure 10. 3D space decomposition (Schön et al., 2013)

In the octree implementation, the index storage table has two columns: OCTREE_CODE (oracle data type RAW, in order to store the cell code, requires 3 bits for each branch), and OCTREE_R- OWID (oracle data type ROWID, 10 bytes in size, in order to store the ROWID of the 3D point geometry).
An octree offers an alternative, but currently no commercially-available SDBMSs support octree indexing (Schön et al., 2013).

4. 3D GEOMETRIES AND 3D OPERATIONS

4.1 Creation and validation

With the utilization and development of dense urban space, true 3D geometric volume primitives are needed to represent 3D parcels with the adjacency and incidence relationship. Validation is a necessary tool to guarantee the output of processing or manipulation GIS operations such as: calculation of the area of polygons; creation of buffers; conversion to other formats; Boolean operations such as intersection, touching, contain, etc. (Ledoux et al., 2009). The definition of the polyhedron/solid given in the ISO standards (ISO, 2003) and implemented with GML (OGC, 2007) is as follows: *A GML solid is the basis for 3-dimensional geometry. The extent of a solid is defined by the boundary surfaces as specified in ISO 19107:2003, 6.3.18. gml:exterior specifies the outer boundary, gml:interior the inner boundary of the solid* (OGC,

2007). To be considered a valid solid, a solid must fulfil several properties or criteria. The most important criteria are: (i) it must be simple (no self-intersection of its boundary); (ii) it must be closed, or ’watertight’; (iii) its interior must be connected; (iv) its boundary surfaces must be properly oriented; (v) its surfaces are not allowed to overlap each other. It should also be noticed that since a solid is formed of 2D primitives (embedded in 3D space), these also have to be valid. For instance, if a surface has a hole (an inner ring), than this ring is not allowed to overlap with the outer boundary of the surface (Ledoux et al., 2009).
From the 3D cadastre perspective, a volumetric primitive is a complete representation of a polyhedron able to support the various calculations and analysis related to the 3D cadastral objects. The volumetric primitives in 3D space need to be mutually exclusive and they need to exhaustively partition the extent of the domain (i.e. no gaps are allowed) (Ying et al., 2015).

SQL Geometry Types
The SQL Geometry Types (OGC, 2010) extend the set of available predefined data types to include Geometry Types. A conforming implementation shall support a subset of the following set of Geometry Types: {Geometry, Point, Curve, LineString, Surface, Polygon, PolyhedralSurface, GeomCollection, MultiCurve, MultiLineString, MultiSurface, MultiPolygon, and MultiPoint}.
OGC (2010) presents a new SQL geometry type – PolyhedralSurface, which is subtyped from Surface, and implements the required constructor routines and interfaces of Surface and MultiSurface. A PolyhedralSurface is a contiguous collection of polygons, which share common boundary segments and which as a unit have the topological attributes of a surface. For each pair of polygons that “touch”, the common boundary shall be expressible as a finite collection of LineStrings. Each such LineString shall be part of the boundary of at most two Polygon patches. The PolyhedralSurface could be a simple, closed polyhedron (OGC, 2011).
Kazar et al. (2008) present Oracle’s data model for storing 3D geometries (following the general OGC/ISO GML3 specifications) and define more specific and refined rules for valid geometries in this model. They show that the solid representation is simpler and easier to validate than the GML model but still retains the representative power.
In Oracle, a simple solid is defined as a ‘Single Volume’ bounded on the exterior by one exterior composite surface and on the interior by zero or more interior composite surfaces. To demarcate the interior of the solid from the exterior, the polygons of the boundary are oriented such that their normal vector always point ‘outward’ from the solid. In addition, each polygon of the composite surfaces has only an outer ring but no inner ring (this is a restriction compared to the GML definitions, but without losing any expression power) (Kazar et al., 2008).
Validation rules/tests for Simple Solids (based on Kazar et al., 2008):

- Single Volume check: The volume should be contiguous.
  - Closedness test: The boundary has to be closed. Necessary condition but not sufficient (Figure 11 left, Figure 12 left, Figure 13 left are invalid).
  - Connectedness test: For sufficiency, volume has to be connected. (Figure 11 right, Figure 12 right, Figure 13 right are valid). This means each component (surface, solid) of the solid should be reachable from any other component.
- Inner-outer check:
  - Every surface marked as an inner boundary should be ’inside’ the solid defined by the exterior boundary.
  - Inner boundaries may never intersect, but only touch under the condition that the solid remains connected (see above).

- Orientation check: The polygons in the surfaces are always oriented such that the normals of the polygons point outward from the solid that they bound. Normal of a planar surface is defined by the right-hand thumb rule (if the fingers of the right hand curl in the direction of the sequence of the vertices, the thumb points in the direction of the normal). The volume bounded by exterior boundary is computed as positive value if every face is oriented such that each normal is pointing away from the solid due to the Green’s Theorem. Similarly, the volume bounded by interior boundary is computed as negative value. If each exterior and interior boundary obeys this rule and they pass connectedness test as well, then this check is passed.
- Element-check: Every specified surface is a valid surface.
- No-inner-ring in polygons: In the composite surfaces of a solid, no inner rings are allowed.

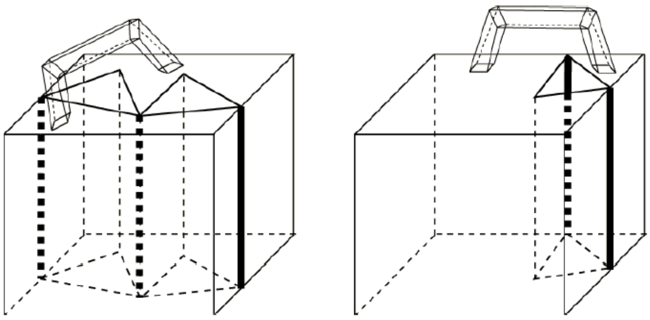

Figure 11. Invalid simple solids becoming valid via adding an additional handle making it possible to travel from one part to another part of the object (completely via the interior). Note: where handle touches the face, a part of the faces is removed (that is an interior ring is added within the exiting face to create the open connection). So, all faces have always (and everywhere) on one side the object and on the other side something else (outside, where the normal is pointing to) (Kazar et al., 2008)

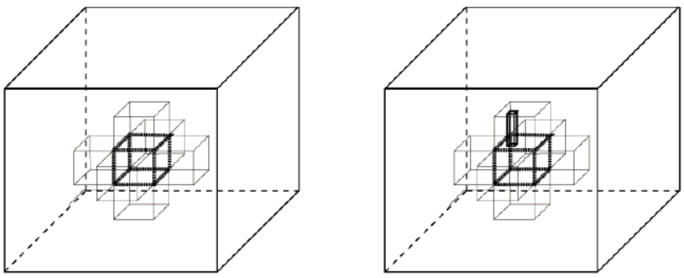

Figure 12. Left: simple solid with 6 internal (cube-shaped) boundaries separating the big cube into two parts (the internal one draw with fat lines is implied by the 6 boundaries of the 6 smaller cube-shaped holes). Therefore the left simple solid is invalid (note that removing one of the 6 holes, makes it valid again). Right: Invalid simple solids of previous figures becoming valid via adding an additional handle making it possible to travel from one part to another part of the object (completely via the interior). Right: the two parts are connected via a ’pipe’ making it a valid simple solid again (Kazar et al., 2008)

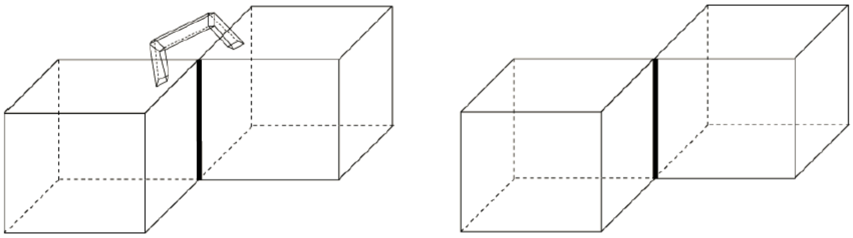

Figure 13. Left: valid simple solid (fat edge still used 4 times), but handle is added through which it is possible to travel from one part to the other part via the interior only, Right: invalid simple solid with one edge being used four times (fat line) (Kazar et al., 2008)

More on valid 3D geometries (for example, composite solids, collections) can be found in Kazar et al. (2008). While definition exists for solids (given by the international standards for geographic information), Ledoux (2014) states that these definitions for solids are ignored by most researchers and software vendors. He states, that several different definitions are indeed used, and none is compliant with the standards: for example solids are often defined as 2-manifold objects only, while in fact they can be non-manifold objects. Exchanging and converting datasets from one format/platform to another is thus highly problematic. Ledoux (2014) presents a methodology to validate solids according to the international standards. He implemented the methodology in a prototype called *val3dity*[2]. The validator for solids in Oracle Spatial permits the validation of solids (although, as explained it is neither according to the ISO rules nor complete) but returns only one error when the solid is not valid: the first one encountered (even if a given solid contains hundreds of errors). The error comes with a code explaining its nature and, when suitable, its location (for example if a shell is not closed the centre of the hole is given). This means that a user has to fix the solid for the error mentioned, and to run the validation function again. This step has to be followed for all the errors present, which can be a rather long and painful process for the user. Ideally, all the errors in a solid should be reported so that a user can fix them in one operation. However, cascading effects when validating should be avoided—one example is if a surface is not a valid polygon in 2D, then the validation of the shell whose boundary contains that surface should not be attempted as it will most likely not be valid. In the prototype val3dity, a "hierarchical validation" is used and efforts are made to avoid cascading errors (Ledoux, 2014).

4.2 3D operations

In the implementation specification, OGC (2011) provides the geometry functions that are not limited to any dimension.

Some of the standard functions given by OGC (Simple feature access – Part 1: Common Architecture (OGC, 2011):

- Envelope ( ): Geometry – The minimum bounding box for the Geometry, returned as a Geometry. Minimums for Z and M may be added.
- IsSimple ( ): Integer – Returns 1 (TRUE) if this geometric object has no anomalous geometric points, such as self intersection or self tangency. The description of each instantiable class will include the specific conditions that cause as instance of that class to be classified as not simple.
- Is3D ( ): Integer – Returns 1 (TRUE) if this geometric object has z coordinate values, etc.

[2] https://github.com/tudelft3d/val3dity *(accessed on 20 August 2016)*

Furthermore, OGC (2011) define methods for testing spatial relations between geometric objects:

- Equals (anotherGeometry: Geometry): Integer – Returns 1 (TRUE) if this geometric object is "spatially equal" to anotherGeometry.
- Intersects (anotherGeometry: Geometry): Integer – Returns 1 (TRUE) if this geometric object "spatially intersects" anotherGeometry.
- Touches (anotherGeometry: Geometry): Integer – Returns 1 (TRUE) if this geometric object "spatially touches" anotherGeometry, etc.

Only DBMS itself decides the implementation of the standard functions (specified by OGC) that considers the third dimension or not (Khuan, 2008).

4.3 3D Spatial Constraints

This section is based on Xu et al. (2016), who demonstrate a new methodology to conceptualise and implement geo-constraints in 3D. At first, constraints are designed and expressed using natural language. Then objects in the sentences are abstracted by geometric primitives, and their interrelationship by topological relationships. By doing so, spatial constraints become more specific and clearer to the others. Following the well-defined spatial types and operations as proposed in the ISO 19107 standard and using various tools, and attempt was made to formalise these constraints using Object Constraint Language (OCL). Finally, the constraints are translated to executable code, for example Procedural Language/Structured Query Language (PL/SQL), and with a small modification realised in the database by trigger mechanisms. OCL is a commonly adopted method of modelling geo-constraints. It is a formal language used to describe the constraints applying to objects, and is part of UML which is preferred concept modelling scheme.
A proposed methodology of modelling 3D geo-constraints can be used as a generic approach for all spatial-related constraints specifications in four stages:

1. Natural Language
2. Geometric/Topological Abstractions
3. UML/OCL Formulations
4. Model Driven Architecture (MDA)
   a. Database PL/SQL Code
   b. Exchange Formal XML
   c. Graphic User Interface ArcGIS

An example of geo-constraint is 'a road cannot cross a building'. Then, in the spatial model, the real world objects can be described by clearly-defined geometric primitives (for example solid, surface, line, point). Here, three things in the text need to be clearly defined, 'what is a building?', 'what does cross mean?', and 'what is a road?' We can model the building using solid geometry and the road surface geometry. And the term 'cross' can be replaced by Nine-Intersection Model (9IM) 'intersect'. The situation the constraint intends to forbid can be rephrased as: 'A surface must not intersect a solid'.

UML/OCL Formulations

Various tools support automatic generation of, for example, SQL script, from UML class diagrams so that an implementation of the model can be created in the database. If OCL constraints can also be integrated to this code generation, the constraints can be integrated to database model and function through the whole lifespan of the database. A challenge of specifying a relationship constraint is that currently there is no a rigorous mechanism in UML2.2 to indicate a constraint. Only when two objects classes are related in the standard way, the constraint can be attached to the association. But when two object classes are not explicitly connected with an association link, the method to mention constraints about their relationships could lead to discussion. For example, in general a road class and a building class may not have an explicit association. However, when some spatial constraint such as minimum distance between them is to be specified, a constraint association between the road class and the building class needs to be considered. Xu et al. (2016) proposed in their research the normal association plus colour ‘red’ as a new type of association link in UML class diagram (see example in Figure 14).

Another difficulty which is somewhat related to the lack of constraint association in UML is that OCL itself does not support constraint expressions that have multiple classes involved. In normal OCL formula, if a constraint related to a different class than the context class needs to be expressed, a name of association end role to navigate from one class to the other is required. For example, to specify the no-intersect rule between a building instance and a road instance, the class ‘Road‘ must be available in the context ‘Building‘. In other words, the class ‘Road‘ should have a property that is of ‘Building‘ type, or ‘Building‘ class should have a property that is of ‘Road‘ type. But in this example of no-intersect between a road and a building, neither ‘Building‘ nor ‘Road‘ has a property to typify each other. So an expression can be (Xu et al., 2016):

```
context Building
inv BldRoadNoIntersect:
   Road.allInstances()  ->  forAll  (r  |  intersect(r.geometry,
geometry) = false)
```

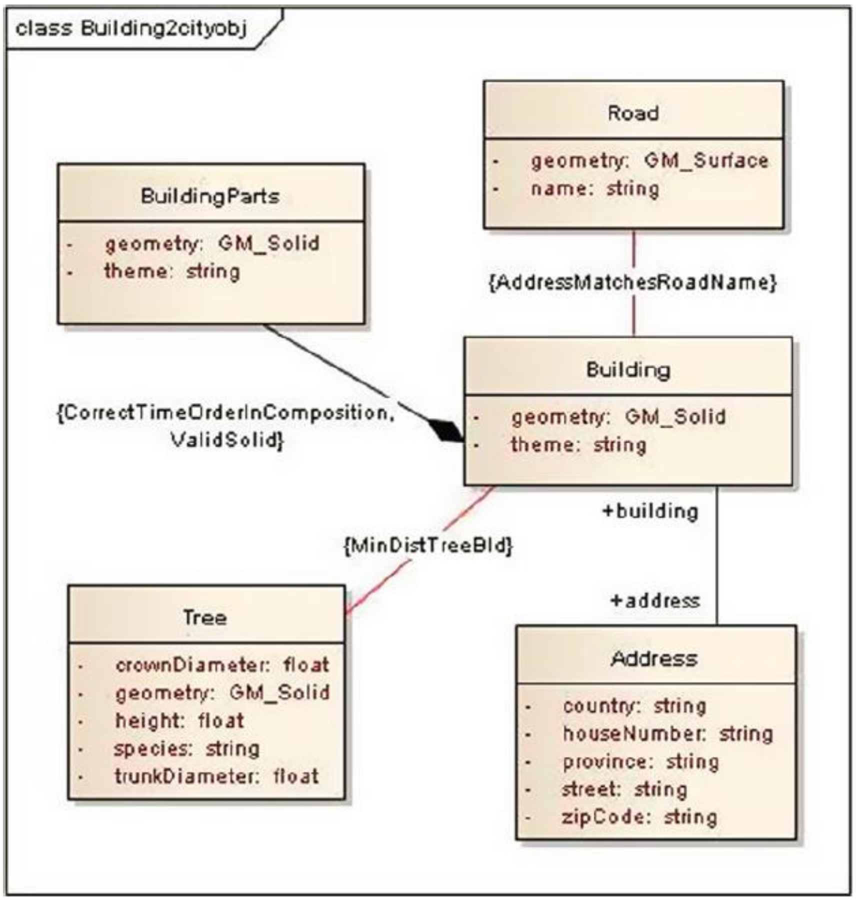

Figure 14. UML model of constraints relevant to building object class (Xu et al., 2016)

Code Generation – Focus on Database PL/SQL Code

The Model Driven Architecture principle, being supported by Object Management Group (OMG), provides a framework to define how models in one domain-specific language (for example UML, OCL) can be translated to models in the other languages. For spatial constraints, the 3D geometries standardised in ISO19107 and 9IM topological names are not yet included in the OCL library.

When a user modifies (create/insert/update/delete) certain datasets and then tries to commit the modification to the database, the trigger will be fired. Once it detects that a constraint is not satisfied in this commitment, it will give an error message to the front-ends and reject the transaction. By this means, a trigger is able to response to the data modification at run-time and guard the database integrity. Given the trigger mechanism, if the OCL expressions are translated into SQL scripts, the spatial constraints check can be carried out by the spatial functions (for example *distance()*, *buffer()*, *intersect()*) supported by the database. In this sense, the power of data maintenance and spatial functions from database can be combined to have 3D geo-constraints integrated in database seamlessly.

However, the existing 3D functions in Oracle Spatial are relatively new and not extended. Many spatial and topological constraint checks cannot be immediately implemented yet. The most useful function in Oracle Spatial database to calculate 3D topological relationships is *SDO_AnyInteract*. It is able to detect if two 3D objects are 'disjoint' or not. But it does not disclose more details about what is happening in the 'non-disjoint' part. For example, two geometries which have ‘touch’ and ‘intersect’ do not make any difference to it. To be able to distinguish them in 3D, a new function named ‘3D_SurfaceRelate’ is developed in this research. Xu et al. (2016) give the examples of constraints on 3D objects. Their methodology (1. Natural language, 2. Geometry/topology, 3. UML/OCL, 4. Implementation) can be applied to many 3D topographic models, such as city models. In their research, 3DCityDB (Kolbe et al., 2009) was selected as a 3D topographic model. The necessary constraints regarding to city objects in 3D space were discovered and described in natural language first. The first attempt to formalise these constraints in UML/OCL – (pseudo 3D geo-OCL) – is explained. The well-defined 3D geometric primitives from ISO19107: 2003 standard - GM_Point, GM_Curve, GM_Surface, GM_Solid and the aggregational and compositional types of them are used as spatial types in UML class diagrams. Further, spatial operators from ISO19107 such as *distance()* and *intersect()*, as well as Oracle functions *inside()* and *validateGeometry()* are used in these formulations. The last stage was a creation of PL/SQL code. Because currently automatic model translation from OCL to SQL is not available, so PL/SQL code was written by hand. The challenges of automatic translation lie on the support of spatial types and operations in OCL standard, multiple class expression of OCL and sufficiency of spatial functions in the database.

5. 3D TOPOLOGY STRUCTURES

Topology is defined as the identification of spatial relationships between adjacent or neighbouring objects (Ellul, 2007). To model 3D topology, a number of 3D topological frameworks have been introduced (Zlatanova 2000). As Zulkifli et al. (2015) mention, these can be distinguished into two types of frameworks:

1. Classification of topological relationships between two objects (for example Egenhofer, 1995; Billen et al., 2002), and
2. Topological structures representing the structural relationship between many primitives and objects (van Oosterom et al 2002, Zlatanova et al 2004).

In the context of the second type of framework, several 3D topological models and approaches have been developed to construct a topologically correct datasets, for example (Penninga and van Oosterom, 2008; Ledoux and Meijers, 2009; Bormann and Rank, 2009; Ghawana and Zlatanova, 2010; Brugman et al., 2011).

5.1 Considering LADM standard

These previously mentioned topological models above have not discussed LADM standard (Zulkifli et al., 2015). A comprehensive land administration model is essential to build the cadastral management system. The LADM (Land Administration Domain Model) provides a conceptual description for a land administration system, including a 3D topology spatial profile (Thompson and van Oosterom 2012).

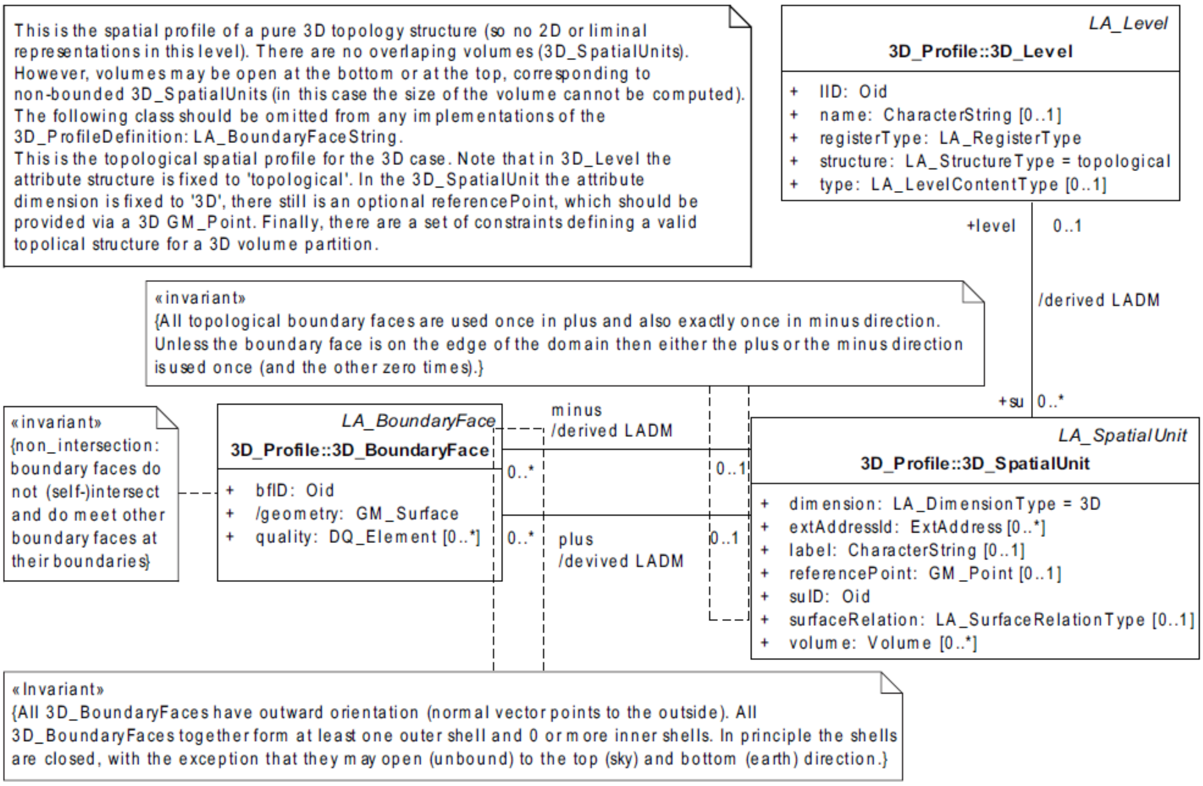

Figure 15. 3D topology based on LADM (ISO, 2012)

The LADM provides conceptual descriptions for land administration, including 3D topology. The LADM also allows for organizing land related data in a standardized and interoperable way to support different types of spatial data. According to the requirements of LADM, topological information alone is not sufficient to describe a 3D spatial unit. Geometrical information must also be associated with each topological primitive; either direct geometries, or indirect (via related topological primitives with geometries). For 3D topology model in LADM as described in Spatial profiles of Annex E7 (ISO, 2012), there are no overlapping volumes (3D_SpatialUnit). However, volumes may be open at the bottom or at the top, corresponding to non-bounded 3D_SpatialUnits (in this case, the size of the volume cannot be computed). Note that in 3D_Level, the attribute structure is fixed to '3D', and there is still an optional referencePoint, which should be provided via 3D GM_Point. There is a set of constraints defining a valid topological structure for a 3D volume partition. In case of the 3D topology representation, a 3D boundary has plus/minus orientation information included in the association to a 3D spatial unit (see Figure 15). All topological boundary faces are used once in plus and also exactly once in minus direction. Unless the boundary face is on the edge of the domain, then either the plus or the minus direction is used once (and the other zero times). The boundary faces do not self-intersect and do meet other boundary faces at their boundaries. All 3D_BoundaryFaces have outward orientation (normal vector points to the outside). All the 3D_BoundaryFaces together form at least one outer shell and zero or more inner shells. In principle, the shells are closed, with the exception that they may open (unbound) to the top (sky) and bottom (earth) direction (Zulkifli et al., 2015).

Zulkifli et al. (2015) review 3D topology within LADM. They review characteristics of the different 3D topological models in order to choose the most suitable model for certain applications. The characteristics of the different 3D topological models are based on several

main aspects (for example space or plane partition, used primitives, constructive rules, orientation and explicit or implicit relationships). The most suitable 3D topological model depends on the type of application it is used for. They conclude, that there is no single 3D topology model best suitable for all types of applications. Therefore, it is very important to define the requirements of the 3D topology model. They further conclude, that based on the reviews of the 3D topological models, a very suitable 3D topology model is the approach based on a Tetrahedral Network (TEN), proposed by Penninga and van Oosterom (2008).
Ying et al. (2015) present an effective straightforward approach to identifying and constructing the valid volumetric cadastral object from the given faces, and build the topological relationships among 3D cadastral objects on-the-fly, based on input consisting of loose boundary 3D faces made by surveyors. These 3D faces as the cadastral boundaries with official identifications are stored in a database. The method does not change the faces themselves and faces in a given input are independently specified. Various volumetric objects, including non-manifold 3D cadastral objects (legal spaces), can be constructed correctly. They also aimed to develop a more direct method of the solid validation process, describing the steps below:

1. To build valid solids at the beginning of object generation to satisfy the validation requirements.
2. If a valid solid is built and the sets of solids directly there is no need to validate its existence afterwards.

They propose a data model oriented towards the application and storage of a 3D cadastral system. Especially, they extend the geometric-topological model in LADM, which is based on ISO 19107, and redesign the model to support non-manifold 3D objects to represent realistic 3D cadastral objects. They propose a method for creation of both 3D volumetric objects – 3D solids and non-manifold solids (shapes with self-touching or hole) along with topological relationships that are already valid. This is important to model some realistic cadastral objects. Also the 3D volumetric objects in relation to the outer complementary space (named by Maximal Minimal Solid) can be generated. The presented approach ensures volumetric objects (polyhedral shapes) that satisfy the valid solid characteristics: face-based construction, closeness and uniqueness. Against the mainstream methods, that require one to assume that the shapes (solids) already exist in the 3D object and then test to see if this existence assumption holds, in the proposed method this assumption step is no longer required as a necessary research process. The input faces themselves are stable and they are independently specified. This direct 3D volume construction conforms to normal sequential data flow and business logic to provide valid 3D volumetric objects for 3D cadastral systems without the need for a post-production validity check.

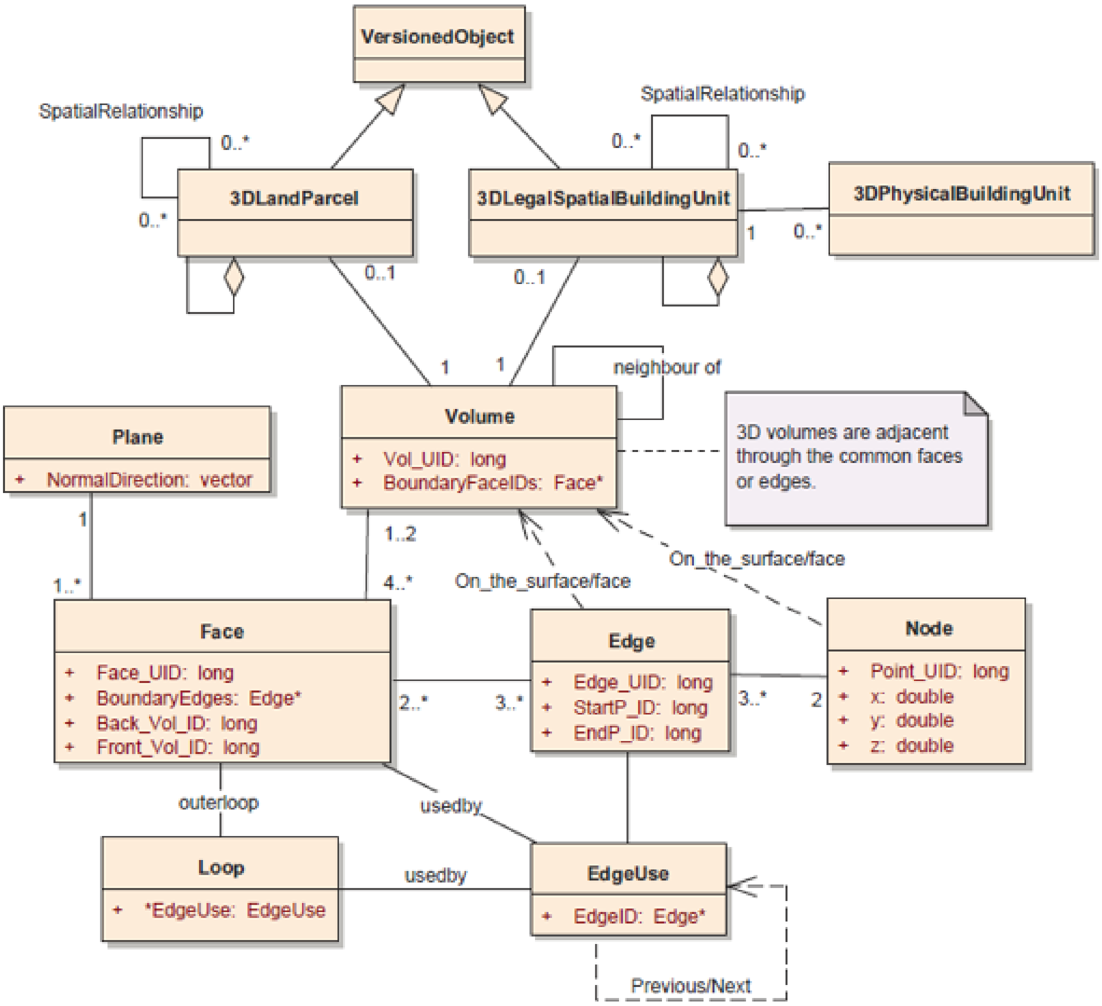

Figure 16. Data model in the prototype system (Ying et al., 2015)

The algorithm is capable of supporting various 3D shapes and non-manifold volumetric objects with holes or caves, and causes no problems with regard to the topological consistency. Real 3D volumetric objects are constructed first with the input faces, storing the references in the 3D topological model (see Figure 16). A valid volume is made up of and closed by at least four faces with their normal directions. A class Plane is designed to emphasize the face's normal direction, which means that every face used in the body is only a half-plane face. A 3D volume is a 3D primitive to describe the volumetric object and is basically incident to faces, the lower dimensional 2D geometric primitive. The volumetric model is defined as a seamless 3D space with interior orientation, and commonly its shells which, closed and made up of the faces, together completely separate the interior and exterior of the volume; volumes cannot intersect and penetrate mutually. An important condition of Face is that its normal direction points outward or inward to the volume, which is essential for volume construction. The face's normal direction determines the interior orientation of the 3D volume, and Class Face is an oriented facet or patch with one outer loop, and zero or more inner loops. In general, the term face denotes a simple flat face that is used to define a part of the boundary.
Ding et al. (2016) propose a modelling approach for the 3D cadastral object based on extrusion. The approach does not allow overlapping among footprints which are used to construct one or

more 3D objects. Based on this approach, one can extract 2D topological features from 2D footprints. Then 2D topological features and height values are used to present topological features. Using 2D feature to present 3D feature can save storage space. They used this approach in a case study and conclude that there is still need for a lot of practice to verify its availability for 3D cadastre.

6. FROM THEORY TO PRACTICE

6.1 General 3D geometry/topology capabilities

Due to the complexity of real-world spatial objects, various types of representations (for example vector, raster, constructive solid geometry, etc.) and spatial data models (topology, and geometry) have been investigated and developed. Promising developments were observed in the SDBMSs domain where more spatial data types, functions and indexing mechanism were supported. In this respect, SDBMSs are expected to become a critical component development of an operational 3D GIS. However, the native 3D support at SDBMS level has to be achieved (Khuan et al., 2008). Mostly all the main spatial database management systems (for example Oracle Spatial, PostgreSQL/PostGIS, Microsoft SQL server) support the Simple Feature Access international standard supporting 3D geometries (Janečka and Kára, 2012).

6.2 Oracle Spatial

The spatial features in Oracle Spatial consist of a set of object data types, type methods, and operators, functions, and procedures that use these types. A geometry is stored as an object, in a single row, in a column of type SDO_GEOMETRY. Spatial index creation and maintenance is done using basic DDL (CREATE, ALTER, DROP) and DML (INSERT, UPDATE, DELETE) statements. The text in this part is mostly based on the official Oracle Spatial 12g documentation[3].

Geometry types

A geometry (in Oracle Spatial) is an ordered sequence of vertices that are connected by straight line segments or circular arcs. The semantics of the geometry are determined by its type. Oracle Spatial supports several primitive types, and geometries composed of collections of these types, including two-dimensional: points and point clusters, line string, n-point polygons, arc line strings (all arcs are generated as circular arcs), arc polygons, compound polygons, compound line string, circles, optimized rectangles. Spatial also supports the storage, indexing (R-tree) and retrieval of three-dimensional and four-dimensional geometric types, where three of four coordinates are used to define each vertex of the object being defined. The three-dimensional spatial data can include: points, point clouds (collection of points), lines, polygons, surfaces, and solids.

[3] http://docs.oracle.com/database/121/SPATL/create-index.htm *(accessed on 19 September 2017)*

Table 1. SDO_GEOMETRY attributes for three-dimensional geometries (*here only Solid and Multisolid are mentioned*)

Type of 3D Data	SDO_GTYPE	Element Type, Interpretation on SDO_ELEM_INFO
Solid	3008	Simple solid formed by a single closed surface: one element type (*SDO_ETYPE, see table 2*) 1007, followed by one element type 1006 (the external surface) and optionally one or more element type 2006 (internal surfaces) Composite solid formed by multiple adjacent simple solids: one element type 1008 (holding the count of simple solids), followed by any number of element type 1007 (each describing one simple solid)
Multisolid	3009	Element definitions for one or more simple solids (element type 1007) or composite solids (element type 1008)

Table 2. Values and semantics in SDO_ELEM_INFO

SDO_ETYPE	SDO_INTERPRETATION	Meaning
1006 or 2006	*n* > 1	Surface consisting of one or more polygons, with each edge shared by no more than two polygons. A surface contains an area but not a volume. The value n in the Interpretation column specifies the number of polygons that make up the surface. The next n triplets in the SDO_ELEM_INFO array describe each of these polygon subelements. A surface must be three-dimensional.
1007	*n* = 1 or 3	Solid consisting of multiple surfaces that are completely enclosed in a three-dimensional space, so that the solid has an interior volume. A solid element can have one exterior surface defined by the 1006 elements and zero or more interior boundaries defined by the 2006 elements. The value n in the Interpretation column must be 1 or 3. Subsequent triplets in the SDO_ELEM_INFO array describe the exterior 1006 and optional interior 2006 surfaces that make up the solid element. If n is 3, the solid is an optimized box, such that only two three-dimensional points are required to define it: one with minimum values for the box in the X, Y, and Z dimensions and another with maximum values for the box in the X, Y, and Z dimensions.

Spatial Indexing
A spatial index (that is, a spatial R-tree index) must be created on each geometry column in the tables for efficient access to the data. For example, the following statement creates a spatial index named *territory_idx* using default values for all parameters:

```
CREATE INDEX territory_idx ON territories (territory_geom)
INDEXTYPE IS MDSYS.SPATIAL_INDEX;
```

Spatial indexes can be built on two, three, or four dimensions of data. The default number of dimensions is two. To have any functions, procedures, or operators consider three dimensions, one must specify *PARAMETERS ('sdo_indx_dims=3')* in the CREATE INDEX statement when creating the spatial index on a spatial table containing for example geographic 3D data (longitude, latitude, ellipsoidal height). If one does not specify that parameter in the CREATE INDEX statement, a two-dimensional index is created.
The following statement creates a 3D spatial index named 3Dparcel_idx:

```
CREATE INDEX 3Dparcel_idx ON 3Dparcels (3Dparcel_geom) INDEXTYPE
IS MDSYS.SPATIAL_INDEX

PARAMETERS ('sdo_indx_dims=3');
```

A partitioned spatial index can be created on a partitioned table. A spatial index cannot be created on an index-organized table[4].

Extending Spatial Indexing Capabilities
Oracle Spatial enables the creation and use of spatial indexes on objects other than a geometry column. The SDO_GEOMETRY object can be embedded in a user-defined object type, and the geometry attribute of that type can be indexed. Further, one can create and use a function-based index where the function returns the SDO_GEOMETRY object.

Coordinate Reference System
The Oracle Spatial support for three-dimensional coordinate reference systems complies with the EPSG[5] model. There are two categories of three-dimensional coordinate reference systems: those based on ellipsoidal height (geographic 3D) and those based on gravity-related height (compound).

Geographic 3D Coordinate Reference Systems
A geographic three-dimensional coordinate reference system is based on longitude and latitude, plus ellipsoidal height. The ellipsoidal height is the height relative to a reference ellipsoid, which is an approximation of the real Earth. All three dimensions of the Coordinate Reference System (CRS) are based on the same ellipsoid.

[4] http://docs.oracle.com/database/121/SPATL/create-index.htm *(accessed on 19 September 2017).*
[5] The IOGP's EPSG Geodetic Parameter Dataset is a collection of definitions of coordinate reference systems and coordinate transformations which may be global, regional, national or local in application.. More on http://www.epsg.org/EPSGhome.aspx (*accessed on 19 September 2017*).

Compound 3D Coordinate Reference Systems

A compound three-dimensional coordinate reference system is based on a geographic or projected two-dimensional system, plus gravity-related height. Gravity-related height is the height as influenced by the Earth's gravitational force, where the base height (zero) is often an equipotential surface, and might be defined as above or below "sea level."

Gravity-related height is a more complex representation than ellipsoidal height, because of gravitational irregularities such as the following:

- Orthometric height - Orthometric height is also referred to as the height above the geoid. The geoid is an equipotential surface that most closely (but not exactly) matches mean sea level. An equipotential surface is a surface on which each point is at the same gravitational potential level. Such a surface tends to undulate slightly, because the Earth has regions of varying density. There are multiple equipotential surfaces, and these might not be parallel to each other due to the irregular density of the Earth.
- Height relative to mean sea level, to sea level at a specific location, or to a vertical network warped to fit multiple tidal stations. Sea level is close to, but not identical to, the geoid. The sea level at a given location is often defined based on the "average sea level" at a specific tidal gauge.

Using ellipsoidal heights enables Oracle Spatial to perform internal operations with great mathematical regularity and efficiency. Compound coordinate reference systems, on the other hand, require more complex transformations, often based on offset matrixes. Some of these matrixes have to be downloaded and configured. Furthermore, they might have a significant footprint, on disk and in main memory.

One can create a customized compound coordinate reference system, which combines a horizontal CRS with a vertical CRS (the horizontal CRS contains two dimensions, such as X and Y or longitude and latitude, and the vertical CRS contains the third dimension, such as Z or height or altitude). It means, that Oracle Spatial also supports 3D Cartesian coordinate reference systems (3D Geocentric). In this system, a point P is referred to by three real numbers (coordinates), indicating the positions of the perpendicular projections from the point to three fixed perpendicular graduated lines, called the axes which intersect at the origin.

Oracle Spatial also supports a local coordinate reference system. These refer to coordinate systems that are specific to an application. Several local coordinate systems are predefined and included with Spatial in the *SDO_COORD_REF_SYS* table. These supplied local coordinate systems, whose names start with Non-Earth, define non-Earth Cartesian coordinate systems based on different units of measurement (Meter, Millimeter, Inch, and so on).

6.3 PostGIS

PostGIS is a spatial database extender for PostgreSQL object-relational database. It adds support for geographic objects allowing location queries to be run in SQL. In addition to basic location awareness, PostGIS offers many features rarely found in other competing spatial databases such as Oracle Locator/Spatial and SQL Server. PostGIS adds extra types (geometry, geography, raster and others) to the PostgreSQL database. The text in this part is mostly based on the official PostGIS 2.3.4 documentation[6].

It also adds functions, operators, and index enhancements that apply to these spatial types. These additional functions, operators, index bindings and types augment the power of the core

[6] http://postgis.net/docs/manual-2.3/index.html (*accessed on 19 September 2017*)

PostgreSQL DBMS, making it a fast, feature-plenty, and robust spatial database management system.
The GIS objects supported by PostGIS are a superset of the "Simple Features" defined by the OGC. PostGIS supports all the objects and functions specified in the OGC "Simple Features for SQL" specification. PostGIS extends the standard with support for 3DZ, 3DM and 4D coordinates.
Some PostGIS functions related to solids:

- ST_IsSolid – Tests if the geometry is a solid. No validity check is performed.
- ST_MakeSolid – Casts the geometry into a solid. No check is performed. To obtain a valid solid, the input geometry must be a closed Polyhedral Surface or a closed TIN.
- ST_Volume – Computes the volume of a 3D solid. If applied to surface (even closed) geometries will return 0.

More information about all the spatial functions in PostGIS can be found in its official documentation.

Spatial Indexing
PostgreSQL/PostGIS supports three kinds of indexes by default: B-Tree indexes, R-Tree indexes, and GiST indexes. GiST is a generic form of indexing. In addition to GIS indexing, GiST is used to speed up searches on all kinds of irregular data structures (integer arrays, spectral data, etc.) which are not amenable to normal B-Tree indexing. The syntax for building a GiST index on a "geometry" column is as follows:

```
CREATE INDEX [indexname] ON [tablename]
USING GIST ( [geometryfield] );
```

The above syntax will always build a 2D-index. To get the n-dimensional index supported in PostGIS 2.0+ for the geometry type, one can create one using this syntax:

```
CREATE INDEX [indexname] ON [tablename]
USING GIST ([geometryfield] gist_geometry_ops_nd);
```

GiST indexes have two advantages over R-Tree indexes in PostgreSQL. Firstly, GiST indexes are "null safe", meaning they can index columns which include null values. Secondly, GiST indexes support the concept of "lossiness" which is important when dealing with GIS objects larger than the PostgreSQL 8K page size. Lossiness allows PostgreSQL to store only the "important" part of an object in an index - in the case of GIS objects, just the bounding box. GIS objects larger than 8K will cause R-Tree indexes to fail in the process of being built.

BRIN Index
BRIN stands for "Block Range Index" and is a generic form of indexing that has been introduced in PostgreSQL 9.5. BRIN is a lossy kind of index, and its main usage is to provide a compromise for both read and write performance. Its primary goal is to handle very large tables for which some of the columns have some natural correlation with their physical location within the table. In addition to GIS indexing, BRIN is used to speed up searches on various kinds of regular or irregular data structures (integer, arrays etc.). Once a GIS data table exceeds a few thousand rows, one will want to build an index to speed up spatial searches of the data

(unless all searches are based on attributes, in which case one will want to build a normal index on the attribute fields). GiST indexes are really performant as long as their size doesn't exceed the amount of RAM available for the database, and as long as one can afford the storage size, and the penalty in write workload. Otherwise, BRIN index can be considered as an alternative. The idea of a BRIN index is to store only the bounding box englobing all the geometries contained in all the rows in a set of table blocks, called a range. Obviously, this indexing method will only be efficient if the data is physically ordered in a way where the resulting bounding boxes for block ranges will be mutually exclusive. The resulting index will be really small, but will be less efficient than a GiST index in many cases.
Building a BRIN index is way less intensive than building a GiST index. It's quite common to build a BRIN index in less time than a GiST index would have required. As a BRIN index only store one bounding box for one to many table blocks, it is common to consume up to a thousand time less disk space for this kind of indexes[7].

Coordinate Reference Systems
The *SPATIAL_REF_SYS* table is a PostGIS included and OGC compliant database table that lists over 3000 known spatial reference systems and details needed to transform/reproject between them. The proj.4 library[8] does not contain all known projections and it is possible to define custom projections with proj.4 constructs.

6.4 3D topology

In the widely used SDBMSs such as Oracle Spatial, PostGIS, ESRI Geodatabase, 2D topology is well supported and documented. However, in most of current SDBMSs, 3D topology is not natively supported. So it is necessary to construct and store custom topology (see chapter 5 3D Topology structures).

6.4.1 Tetrahedral networks for modelling 3D topographic objects

For storing and modelling three-dimensional topographic objects (for example buildings, roads and terrain), tetrahedralisation have been proposed as an alternative to boundary representations. Penninga (2005) presented a modelling approach for 3D topography modelling based on tetrahedral network (TEN). The approach is based on two fundamental observations:

- The ISO 19101 Geographic information - Reference model defines a feature as an ’abstraction of real world phenomena’. These real world phenomena have by definition a volumetric shape. In modelling, often a lesser-dimensional representation is used in order to simplify the real world. Fundamentally there are no such things as point, line or area features; there are only features with a point, line or area representation (at a certain level of abstraction/generalization).
- The real world can be considered to be a volume partition. A volume partition can be defined (analogously to a planar partition) as a set of non-overlapping volumes that form a closed modelled space. As a consequence objects like ’air’ or ’earth’ are explicitly part of the real world and thus have to be modelled.

[7] http://postgis.net/docs/manual-2.3/using_postgis_dbmanagement.html#idm2221 (*accessed on 19 September 2017*)
[8] proj.4 is a standard UNIX filter function which converts geographic longitude and latitude coordinates into cartesian coordinates (and vice versa), and it is a C API for software developers to include coordinate transformation in their own software. More on http://proj4.org/ (*accessed on 19 September 2017*)

Four types of topographic features can be determined: 0D (point features), 1D (line features), 2D (area features) and 3D (volume features). For each type of feature simplexes of corresponding dimension are available to represent the features with, i.e. nodes, edges, triangles and tetrahedrons. A great advantage of using these simplexes is the well-defined character of the mutual relationships: a kD simplex is bounded by (k+1) geometrically independent simplices of (k-1) dimension (Pilouk, 1996). The important advantage of simplexes is the flatness of the faces, which enables one to describe a face using only three points. The next advantage is that every simplex, regardless its dimension, is convex, thus making convexity testing unnecessary (Penninga, 2005).
The topographic model is stored as a full TEN. The process of modelling topographic features consists of four discernible steps:

1. Start with four initial tetrahedrons, two ’air’ and two ’earth’ tetrahedrons;
2. Refine the earth’s surface by inserting height information from a DEM;
3. Refine ’air’ and ’earth’ tetrahedrons in case of ill-shaped tetrahedrons by insertion of Steiner points;
4. Add real topographic features.

Triangulating or tetrahedronizing the features one-by-one before insertion in the topographic model reduces computational complexity and thus saves computer time. The results need to be inserted into the full topographic model. This requires the use of an incremental algorithm to avoid recomputing the whole model. As the complete topographic model (the TEN) will be stored in a spatial database, it is necessary to implement the incremental algorithm within the database. As a result a full DBMS approach is required, instead of using the database just to store results of the computations (Penninga, 2005).
Penninga (2008) proposed a DBMS data structure for storage of a constrained TEN. His simplicial complex-based method requires only explicit storage of tetrahedrons, while simplexes of lower dimensions (triangles, edges, and nodes), constraints and topological relationships can be derived in views. In this implementation, simplexes are encoded by their vertices. He demonstrates, that storage requirements for 3D objects in tetrahedronised form (excluding the space in between these objects) and 3D objects stored as polyhedrons are in the same order of magnitude.
A TEN has favourable characteristics from a computational point of view. All elements of the tetrahedral network consist of flat faces (important for clear inside/outside decisions), all elements are convex and they are well defined, thus allowing relatively easy implementation of operations, such as validation of 3D objects (Penninga, 2008). A full volumetric approach contributes not only to improved analytical and validation capabilities, but also enables future integration of topography and other 3D data within the same volume partition (Penninga, 2008).
Since the edit operations act as locally as possible, the resulting tetrahedronization is not necessarily of the best quality. To overcome this drawback, periodical quality improvements need to be made. Three types are distinguished: operators that add vertices, operators that remove vertices and operators that modify the TEN configuration through flips. Often, a complete TEN rebuild might be feasible to optimise TEN quality (Penninga, 2008).
Ledoux and Meijers (2013) proposed an alternative data structure for storing tetrahedralisation in a DBMS (see Figure 18). It is based on the idea of storing only the vertices and stars of edges; triangles and tetrahedra are represented implicitly. The structure permits one to store attributes for any primitives, and has the added benefit of being topological, which permits one to query it efficiently.

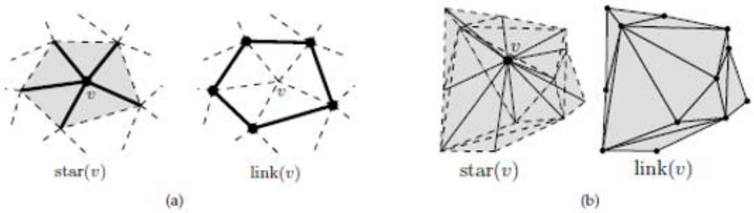

Figure 17. The star and the link of a vertex v in (a) 2D and (b) 3D (Ledoux and Meijers, 2013)

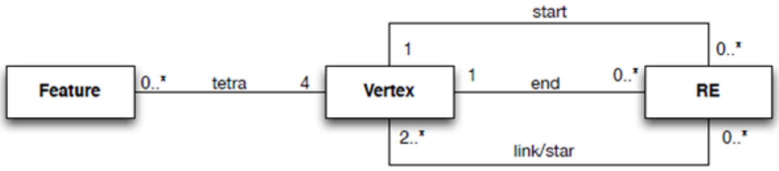

Figure 18. The UML diagram of the data model for star-based data structure (Ledoux and Meijers, 2013)

The strong point of the star-based structure is that it can be easily implemented in any DBMS supporting variable length arrays with two simple tables, and that no complex spatial index is needed (Ledoux and Meijers, 2013).

6.5 Point clouds and TINs

ESRI Geodatabase allows storing triangulated irregular network (TIN) as a planar graph where nodes are connected by edges to form triangles. Edges connect to nodes that are close to one another.

PostGIS has constructors for creating 3D geometry and has an extension and loader *pgpointcloud*[9] for storing point cloud data. It also includes extension for casting between point cloud data type and PostGIS geometry. TIN in PostGIS is modelled as a special case of polyhedral surface which is collection of adjacent triangles, which is similar to Microsoft SQL Server.

From the data structures point of view, Oracle Spatial is an example of SDBMS providing suitable data structures and mechanisms directly for TINs and point clouds. When the available specialized object types are used, a point cloud can be stored in a single row, in a single column in a user-defined table in Oracle Spatial. These object types related to point clouds and TINs are elaborated for example in (Janečka and Kára, 2012).

Martinez et al. (2014) used MonetDB and PostgreSQL with the point cloud data to understand the impact of the point cloud data on the different layers of a DBMS. It touches key issues from (adaptive) data loading to optimization of queries over point clouds. The results obtained through a micro benchmark illustrate both the capabilities to handle point cloud queries efficiently, as well as the relative merits of traditional index structures and compression techniques on the performance characteristics. They conclude, that MonetDB can be considered more modern than PostgreSQL, because it is designed from an in-memory perspective and relies on the operating system to move data between the storage hierarchies in an efficient

[9] https://github.com/pgpointcloud/pointcloud *(accessed on 21 August 2016)*

manner. All queries are also highly parallel, using the cores available wherever possible. On the contrary, PostgreSQL represents the traditional buffer-based and iterator query engine approach. Tuning the buffer size to use all available memory by itself does not help because the logic of chasing data in buffers remains. Further they mention, that PostgreSQL does not by default support multi-core query processing.
van Oosterom et al. (2015) designed a point cloud benchmark based on requirements from different groups of users within government, industry and academia. They analysed various data management systems: PostgreSQL, MonetDB, Oracle, and LAStools. They stated that the Oracle Exadata[10] with flat table model proved to be a very effective environment, both with respect to data loading and querying. Due to the massive parallel hardware engineered towards DBMS support, it was possible to load 23 billion points in less than 4:39 hours and storing the 12 Tb data from LAS files into a 2.2 Tb database (using 'query high' compression). In case of queries returning a very large number of points (from 10 million to over 1 billion), the system outperformed the other platforms.

7. RECENT DEVELOPMENTS OF SPATIAL DATABASES

7.1 nD-array Database Management Systems

Computer memory is inherently linear one-dimensional structure, mapping multi-dimensional data on it can be done in several ways. By far the two most common memory layouts for multi-dimensional array data are row-major and column-major. When working with 2D arrays (matrices), row-major vs. column-major are easy to describe. The row-major layout of a matrix puts the first row in contiguous memory, then the second row right after it, then the third, and so on. Column-major layout puts the first column in contiguous memory, then the second, etc. (Bendersky, 2015).

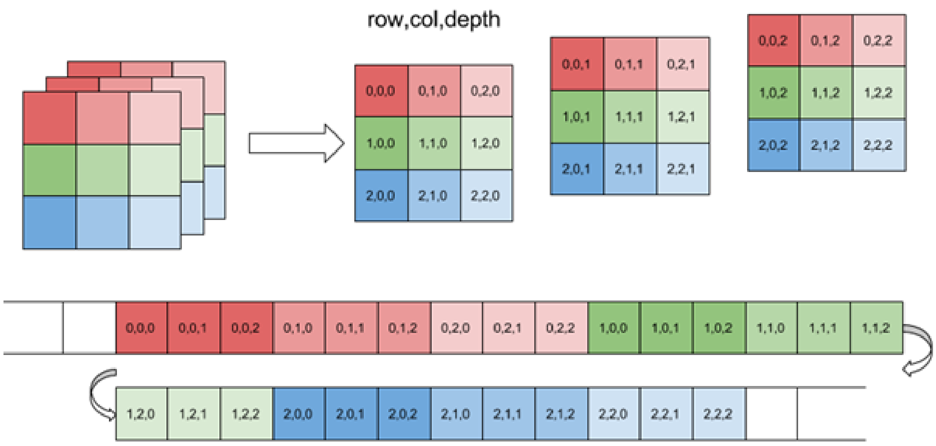

Figure 19. Mapping 3D array with $N_1 = N_2 = N_3$ in row-major (Bendersky, 2015)

[10] http://www.oracle.com/technetwork/database/exadata/overview/index.html *(accessed on 21 August 2016)*

The offset for a given element is:

$$offset = n_3 + N_3 * (n_2 + N_2 * n_1)$$

For example, the offset of the element with indices 2,1,1 is 22 (Bendersky, 2015).
While the database collection types set, list, and record have received in-depth attention, the fourth type, array, is still far from being integrated into database modeling. Due to this lack of attention there is only insufficient array support by today's database technology. This is surprising given that large, multi-dimensional arrays have manifold practical applications in earth sciences (such as remote sensing and climate modeling), life sciences (such as microarray data and human brain imagery), and many more areas (Bauman and Holsten, 2010).
To overcome this, large, multi-dimensional arrays as first-class database citizens have been studied by various groups worldwide. Several formalisms and languages tailored for use in array databases have been proposed and more or less completely implemented, sometimes even in operational use (Bauman and Holsten, 2010). Array Databases close a gap in the database ecosystem by adding modeling, storage, and processing support on multi-dimensional arrays (Baumann and Merticariu, 2015).
In the attempt towards a consolidation of the field Bauman and Holsten (2010) compare four important array database models: AQL, AML, ARRAY ALGEBRA, and RAM. As it turns out, ARRAY ALGEBRA is capable of expressing all other models, and additionally offers functionality not present in the other models. They show this by mapping all approaches to ARRAY ALGEBRA. This establishes a common representation suitable for comparison and allows us discussing the commonalities and differences found. Finally, a feasibility of conceptual array models for describing optimization and architecture was showed.
ARRAY ALGEBRA adopts an algebraic approach to array modeling. The targeted application domains of ARRAY ALGEBRA encompass sensor, image, and statistics data services. However, as stated in Bauman and Holsten (2010), current emphasis is on large-scale Earth Science (Gutierrez and Baumann, 2007) data.

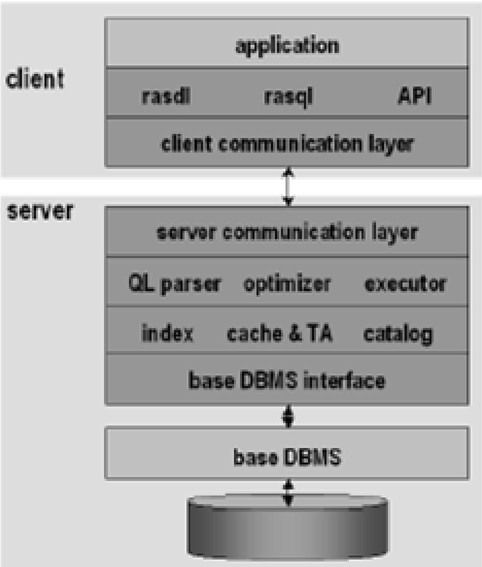

Figure 20. *RasDaMan* system architecture (dark grey) situated between application and base DBMS layers (light grey) (Baumann and Holsten, 2010)

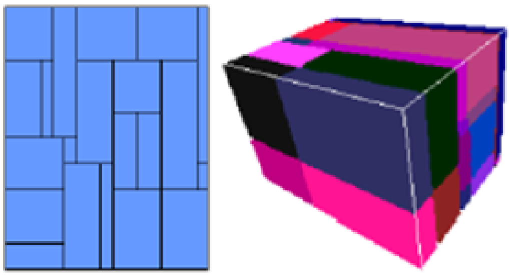

Figure 21. Sample 2-D and 3-D array tilings (Baumann and Holsten, 2010)

The *RasDaMan* array DBMS with its query language, rasql [11], implements ARRAY ALGEBRA. This system is in operational use since many years, among others as the geo raster server of the French National Geographic Institut where an airborne image map of dozen TB size is maintained. The *RasDaMan* implementation employs a middleware architecture where multidimensional arrays are partitioned into multi-dimensional sub-arrays called tiles. These tiles, which represent the units of disk access, are stored in BLOBs (binary large objects) inside some relational or object-oriented database, such as PostgreSQL or O2[12]. A spatial index helps to quickly determine the tiles affected by a query. Query processing relies on tile streaming: Physical query operators follow the open-next-close (ONC) protocol for reading their inputs tile by tile, and likewise they deliver their results in units of tiles. Based on this processing paradigm, the *RasDaMan* architecture follows a conventional multi-user DBMS approach, however, with all components crafted individually to accommodate the special needs of array processing. Array definition and query languages, rasdl and rasql, are available to the application via command line tools, visual tools, and C++ and Java APIs. The client/server communication protocol connects clients to the DBMS server. A dispatcher distributes incoming queries among the *RasDaMan* server processes running. Each server process (see Figure 20) receives queries and parses, optimizes, and executes them. Auxiliary modules include catalogue manager, index manager, as well as cache and transaction manager. For example, the catalogue contains the array and collection type definitions against which semantic checks (like boundary checks for array dimensions not containing open limits) are performed during query analysis. The base DBMS interface layer abstracts from the particularities of the underlying DBMS. Adaptors exist for PostgreSQL, MySQL, Oracle, DB2, Informix, and the file system. Thereby, both array data, *RasDaMan*-internal array metadata, and non-array application data all end up in the same underlying database. As practice shows, this information integration considerable eases database administration (Baumann and Holsten, 2010).
In industrial world, for example Oracle offers the GeoRaster cartridge for 2-D geo raster imagery stored in a database. Instead of a rigorous embedding into SQL there are procedural constructs in PL/SQL which accomplish raster access as well as invocation of a set of predefined functions (Baumann and Holsten, 2010). PostGIS Raster is an extension to PostGIS which supports 2-D raster imagery through map algebra functions; unlike in *RasdaMan*, these are implemented as user-defined data types and, hence, not as tightly integrated and optimizable. PostGIS Raster generally is considered suitable for small and medium size rasters[13]. In the application domain, ARRAY ALGEBRA concepts have had much impact on

[11] http://rasdaman.org/browser/manuals_and_examples/manuals/doc-guides/ql-guide.pdf?order=name *(accessed on 16 August 2016)*
[12] http://www.sai.msu.su/sal/H/2/O2.html *(accessed on 16 August 2016)*
[13] http://lists.osgeo.org/pipermail/postgis-users/2014-April/039024.html *(accessed on 21 August 2016)*

the design of the Open GeoSpatial Consortium (OGC) Web Coverage Processing Service (WCPS) geo service standard (OGC, 2008) and several related OGC standards. Baumann and Holsten (2010) worked on extending the framework beyond arrays towards general meshes so as to allow retrieval on further spatiotemporal scientific data, such as Voronoi-type structures (adaptive grids can be handled already). They also investigated the seamless integration of arrays as first-class abstractions with standard SQL.

The *RasDaMan* system utilizes PostgreSQL as a backend to support point clouds through its WCS interface, thereby unifying grid and point cloud access (Baumann and Holsten, 2010).

In scaling out on point clouds, that are characterized by large numbers of points (going into the billion, and growing), relational databases possibly have a say again. For example, MonetDB[14] shows promising handling of point clouds in its column-store architecture (Martinez et al., 2014).

SciQL (Kersten et al., 2011) is a SQL-query language for science applications with arrays as first class citizens. It provides a seamless symbiosis of array-, set-, and sequence- interpretation using a clear separation of the mathematical object from its underlying storage representation. The language extends value-based grouping in SQL with structural grouping, i.e., fixed-sized and unbounded groups based on explicit relationships between its index attributes. The SciQL architecture benefits from a column store system with an adaptive storage scheme, including keeping multiple representations around for reduced impedance mismatch.

SciDB is an open source data management system intended primarily for use in application domains that involve very large (petabyte) scale array data. SciDB is built to support an array data model and query language with facilities that allow users to extend system with new scalar data types and array operators (Brown, 2010).

Misev and Baumann (2014) proposed a generic model, ASQL, for modelling and querying multi-dimensional arrays in ISO SQL. The model integrates concepts from the three major array models seen today: *RasDaMan*, SciQL, and SciDB. It is declarative, optimizable, minimal, yet powerful enough for application domains in science, engineering, and beyond. ASQL has been implemented and is currently being discussed in ISO for extending standard SQL (Misev and Baumann, 2014).

7.2 File based solutions vs. nD-array database management system

Management of large datasets including storage, structuring, indexing and query is one of the crucial challenges in the era of big data. Liu et al. (2016) benchmarked NetCDF file based solutions and a multidimensional (MD) array database management system applying chunked storage to determine the best solution for storing and querying large hydrological datasets. In total nine criteria are defined to compare MD array DBMSs, as a result SciDB is selected for benchmarking.

NetCDF is notable for its simple data model, ease of use, and portability. However, according to practical experience, traditional NetCDF solutions perform inefficiently in retrieving information from large spatio-temporal datasets for certain queries. This is caused by the way it stores variable values, which is known as contiguous storage structure. Basically, for a grid full of variable values in a certain spatial area, NetCDF stores values into a one-dimensional array according to a row-majored order. When managing large numbers of MD array datasets, it is natural to adopt a DBMS solution as it could provide an easier to use and more scalable alternative (Liu et al., 2016).

[14] https://www.monetdb.org/Home *(accessed on 18 August 2016)*

Within DBMS scope, MD array DBMS is optimized further for MD array data management. It can specify metadata and supports storage of MD arrays. It employs the chunked storage structure which divides a whole dataset into separate chunks with specified chunk sizes. Based on this storage structure, MD array DBMSs then apply specific array addressing and relative offset calculation to index values, which is proved to be of high query efficiency. Hence, Liu et al. (2016) aimed at investigating whether the MD array DBMS can achieve better performance in processing queries on large MD hydrologic datasets than classic non-chunked NetCDF solution and competitive performance when compared to chunked NetCDF-4 file based solution. Their research illustrates that for big hydrological array data management, the properly chunked NetCDF-4 solution without compression is in general more efficient than the SciDB DBMS.

7.3 GPU use and massive parallel architectures for processing large-scale geospatial data

Modern Graphics Processing Units (GPUs) are now capable of general computing (Hennessy and Patterson, 2011). GPUs that are capable of general computing are facilitated with Software Development Toolkits (SDKs) provided by hardware vendors (Zhang et al., 2015c) see Figure 22.

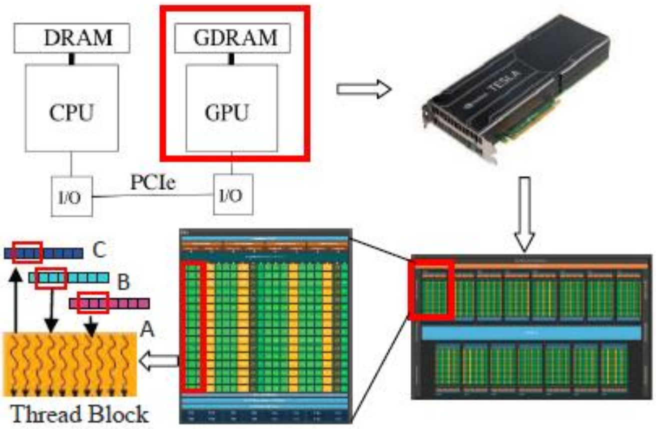

Figure 22. Illustration of GPU hardware Architecture (according to (Zhang et al., 2015c))

While geospatial data management techniques have been provided by both Spatial Databases and Geographical Information Systems (GIS), existing software is incapable of processing large-scale geospatial data for practical applications (Zhang et al., 2014). Quickly evolving processor, storage and networking technologies require new Big Data research to understand how new hardware impacts the performance of large-scale data processing.

In the past few years, the simplicity of the MapReduce computing model and its support in the open source Hadoop system have made it attractive to develop distributed geospatial computing techniques on top of MapReduce/Hadoop (Cary et al., 2009). The success of SpatialHadoop (Eldawy and Mokbel, 2013) and HadoopGIS (Aji et al., 2013) has demonstrated the effectiveness of MapReduce-based techniques for large-scale geospatial data management where parallelisms are typically identified at the spatial partition level which allows adapting traditional serial algorithms and implementations within a partition (Zhang et al., 2015c).

GPU-equipped computing nodes have much higher ratios between floating point computing power (in the order of floating point operations per second (flops), nowadays teraflops (Tflops) and fast growing) and network bandwidth (in the order of Gbps and remains stable) than regular computing nodes at which Hadoop-based systems are targeting. The gap makes efficient and scalable processing of large-scale data challenging, especially for geospatial data, whose processing is both data intensive and computing intensive (Zhang et al., 2015b).
Several techniques for processing large-scale geospatial data have been developed on both single computing nodes and clusters equipped with GPUs (You et al., 2015a; You et al., 2015b; Zhang et al., 2015a; Zhang et al., 2014).
Zhang et al. (2015c) report their work on data parallel designs for several geospatial data processing techniques. By further integrating these GPU-based techniques with distributed computing tools, including Message Passing Interface[15] (MPI) library in the traditional High-Performance Computing (HPC) clusters and newer generation of Big Data systems (such as Impala[16] and Spark[17] for Cloud computing, it is possible to scale the data parallel geospatial processing techniques to cluster computers with good scalability.
While being aware of the complexities in developing a spatial database on GPUs, Zhang et al. (2015c) demonstrated the feasibility and efficiency of GPU-based geospatial processing, especially for large-scale data, developed modules for major geospatial data types and operations that can be directly applied to practical applications and developed a framework to integrate multiple GPU-based geospatial processing modules into an open system that can be shared by the community.

8. DISCUSSION

8.1 Modelling 3D parcels

Beside the non 2-manifold geometries (see chapter 2.1 Vector representation) for representation of 3D parcels there could be a need of further 3D Cadastre specific geometries: partly open solids and curved surfaces (boundaries).
Zlatanova et al. (2006) present design of freeform types to be considered for SQL Implementation Specifications (i.e. for an implementation in DBMS). They implemented the new geometries in Oracle Spatial as individual data types outside the SDO_GEOMETRY model. They showed that non-uniform rational basis spline (NURBS) is a very general representation of freeform shapes and demonstrated that appropriate data types for efficient management of freeform surfaces can be created at DBMS level. They argue, that many issues have to be further investigated. For example, the validation rules for freeform curves and surfaces have to be further specified, relevant functions for support at DBMS level have to be determined, spatial indexing have to be also considered.
Regarding the partly open solids, Thompson and Oosterom (2006) introduced a concept of the regular polytope. Figure 23 shows how a region (“convex polygon”) can be defined as the intersection of a number of half spaces. A regular polytope is then defined as the union of a finite set of (possibly overlapping) non empty convex polytopes (Thompson and Oosterom, 2011).

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[15] http://en.wikipedia.org/wiki/Message Passing Interface *(accessed on 22 August 2016)*
[16] http://impala.io *(accessed on 22 August 2016)*
[17] http://spark.apache.org *(accessed on 22 August 2016)*

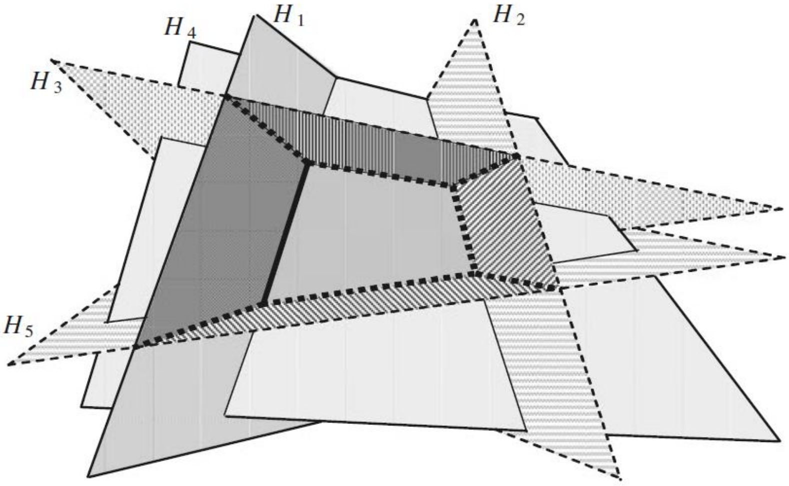

Figure 23. A convex region defined by a set of half spaces (Thompson and Oosterom, 2006)

The regular polytope, since it does not need to be bounded on all sides is a natural representation for a mix of 2D and 3D parcels (Thompson and Oosterom, 2006).

8.2 Validation of 3D solids

Spatial DBMS should enable validation of 3D solids. Ledoux (2014) mentions several possible extensions of validation of 3D solids. For the modelling of 3D buildings, the semantics information can be used. For example, if for instance one surface is labelled as the roof of the building, then an extra validation rule (over the geometry) would be to ensure that the roof is located "above" the surface labelled as the ground floor. Furthermore, the automatic repair of invalid solids could be considered.

8.3 3D Spatial Constraints

Xu et al. (2017) give suggestions regarding the future work dealing with 3D spatial constraints:

- The pseudo 3D Geo-OCL expressions need to be tested in conjunction with the UML diagrams.
- It would be useful to extend OCL code generation tools to enable automatic model translation from OCL (especially spatial constraints) to SQL.
- Further study can be conducted into detecting contradicting (spatial and non-spatial) constraints.
- Corresponding functions in database need to be developed, esp. 3D and solids related, to implement 3D spatial predicates from extended OCL.
- Test the performance of the trigger that uses 3D geometric operators.

8.4 3D topology

As previously elaborated, a suitable 3D topology model for 3D cadastre seems to be an approach based on a Tetrahedral Network (TEN), proposed by Penninga and van Oosterom (2008): the "topological structure to organize tetrahedrons". However, the TEN model need to be synchronized, described in a new spatial profile, with LADM specifications. As mentioned in Zulkifli et al. (2015), the future work is to develop a conceptual model of the TEN based on

LADM standard. Then, the proposed conceptual models (i.e. 2D and 3D topology) should be translated into physical model to develop a prototype cadastral registration.
A full topological model for the 3D cadastre, land planning and management is needed for the following reasons: (1) to utilize the surveying boundaries to generate the 3D cadastral objects (the term "volumetric model" is used geometrically and topologically); (2) to represent the 3D volumetric objects with high quality, and consistent topology without intersection; and (3) for rapid topological queries necessary for real-time user interaction and management (Ying et al., 2015).
Another important aspect is the development of (spatial) indexes for topological models. Last but not least, operations on topological models, including conversion to geometric models, are important (Breunig and Zlatanova, 2011).
The legal and physical object proposed by (Aien 2015 et al) and the 9-intersection model by (Egenhofer and Herring, 1990) to define spatial relationships can advance the 3D topological analysis related to boundaries. To define the boundaries of a 3D RRR, the adjacency matrix for representing the relationship between legal and physical objects can be constructed. In this approach, one could analyse the 3D RRRs in relation to the physical objects and form the adjacency matrix. This will enable support of a range of common queries about the 3D RRR boundaries. This includes queries such as: "What are the 3D rights associated with this property?", "What are the rights associated with an apartment unit?" and "what is the association of an infrastructure with the surrounding RRRs?"

8.5 Point clouds and TINs

Van Oosterom et al. (2015) state that at least two closely related level of standardization must be considered: (a) Database Structure Query Language (SQL) extension for point clouds, and (b) Web Point Cloud Services (WPCS) for progressive transfer based on multi-scale or vario-scale LoD.
Janečka and Kára (2012) suggest to extend the point cloud and TIN related data structures available in production spatial databases to enable storage of additional non-spatial attributes (semantic) related, for example to the particular point (or set of points). Such information can be then used, for example, during the update of the stored 3D geometries directly inside the spatial database.

8.6 Usage of GPU clusters for processing geospatial data

Balancing latency and throughput has profound implications in Big Data research. While traditional parallel and distributed databases are mostly targeted at reducing data processing latency for moderately sized datasets, Big Data systems need to take ownership costs and energy consumption into consideration. Using large quantities of small processors to achieve similar throughputs while reducing energy footprint is becoming an increasingly important topic in Big Data research (Zhang et al., 2015b). Motivated by the increasing gap between the computing power of GPU-equipped clusters and network bandwidth and disk I/O throughput, Zhang et al., (2015b) proposed a low-cost prototype research cluster made of NVidia TK1 SoC[18] boards that can be interconnected with standard 1 Gbps network to facilitate Big Data research. They evaluate the performance of the tiny GPU cluster for spatial join query processing on large-scale geospatial data. Experiments on point-in-polygon test based spatial join using two real world applications with tens to hundreds of millions of points and tens of

[18] http://www.nvidia.com/object/jetson-tk1-embedded-dev-kit.html *(accessed on 21 August 2016)*

thousands of polygons have demonstrated the efficiency of the solution when compared with SpatialSpark. The future work should incorporate not only including processors, but also memory, disk and network components. Furthermore, the performance of GPU cluster should be evaluated using more real world geospatial datasets and applications, for example, distance and nearest neighbour based spatial joins (Zhan et al., 2015b).
In the age of Big Data it is not sufficient any longer that each research domain pursues its own ways of finding solutions, often reinventing the wheel or, conversely, inventing inadequate wheels. Specifically, the geoinformatics domain and core computer science domains like databases, Web services, programming languages, and supercomputing, share challenges seen from different angles. It is not too infrequent that similar ideas appear in different fields. For example, array databases offer declarative query languages on large n-D arrays which internally are partitioned for efficient access to subsets. SciHadoop is an approach independent from databases where an array-tuned query language is put on top of Hadoop. Data formats like TIFF and NetCDF also support the concept of array partitioning. It is worthwhile, therefore, to extend this small, focused survey into a larger one incorporating more domains and also implementation aspects. Fostering exchange, therefore, seems promising (Baumann, 2014).

9. CONCLUSIONS

The use of land in the vertical dimension has necessitated the creation and maintenance of 3D cadastre. The use and generation of 3D data, both cadastral and non-cadastral has increased greatly. The major technological and business drivers for the growth are sensor and hardware capabilities for capture and utilisation of large point clouds; 3D visualisation is mainstream but 3D analysis not yet; managing 3D data and bridging the gap between point cloud and GIS, CAD BIM systems; and the necessity to use 3D data to better describe the real world. Organisations are not yet in 3D because 3D modelling is more complex than 2D, converting 2D data to 3D is difficult, it requires migration from a simple to a complex data structure, economic viability, and a lack of user friendly 3D analyses tools that are yet to be developed.
Three-dimensional data models and their topological relationships are two important parts of 3D spatial data management. The expectations from a 3D spatial system are to enable data models that handle a large variety of 3D objects, automated data quality checks, search and analysis, data dissemination, 3D rendering and visualisation and close linkages to standards. Although a lot of work has been completed on defining a 2D or 3D vector geometry in standards by the OGC and the ISO, it is still insufficient to define 3D cadastral objects. 3D objects have a more rigorous definition for cadastral purposes. For a volumetric 3D cadastral object, for example, the polyhedron needs to satisfy characteristics such as closeness, interior connection, face construction and proper orientation. The LADM addresses many of the issues in 3D representation and storage of 3D data in a DBMS. It allows in-row storage of 3D data in a mixed 2D-3D database allowing for fast retrievals and analysis; it allows for 3D data to be stored in different levels of detail, overlapping 2D footprint of 3D objects, and supports liminal parcels, as well as allows attribution of different boundary lines and faces. However, an identified issue is the duplication of definition of boundaries for separate spatial units.
Three-dimensional objects can be represented using voxels (volumetric pixels) as it brings advantages in object representation, object count and volume, 3D operations and simple analysis, better representation of the various levels of detail of a 3D city model, and representing 3D as a solid instead of point, line and polygon. The challenges to this are the storage and efficient handling by current spatial databases, although there are GIS systems that are working

towards creating a column store structure to accommodate voxels. 3D objects can also be represented as a point cloud. LiDAR point clouds could assist to either be a reference framework of as-constructed features, or a 3D data acquisition tool for 3D physical objects, or a verification tool for pre-existing BIMs or other models. Point cloud data can be for data such as administrative, vector, raster, temporal etc. and a generic DBMS should be able to combine these data for a point cloud data type with characteristics such as xyz values, attributes per point, spatially coherent data organisation, efficient storage and compression, data pyramid support for multi-scale or vario-scale support, temporal support, query accuracy over a range of dimensions, analytical functions and parallel processing.

Spatial indexing is used by databases to improve search speeds, of the three types of indexes namely B-Tree, R-Tree and GiST, the latter two are found to be useful for GIS data. As with 2D geometry, 3D volumetric primitives would need to satisfy the adjacency and incidence (gaps and overlaps) relationship so that they are mutually exclusive and spatially exhaustive in the domain. While standards and definitions for solids such as the PolyhedralSurface in the SQL Geometry Types of OGC as well as other definitions for solids exist, they are not utilised very well currently and do not comply very well with standards. Validation of such solids and exchange of datasets between formats and platforms are highly problematic and do not usually follow any standards and error reports are usually cascading rather than in a single report making it very cumbersome to deal with errors individually.

Operations on and amongst 3D objects have been described by OGC, such as 3D architecture (Envelope(), IsSimple(), Is3D() etc.) and Spatial relationships (Equals(), Intersects(), Touches() etc.), however existing DBMS often implement them differently. 3D topological structures are an important consideration in a 3D cadastral DBMS. Topological relationships between neighbouring parcels can be between two objects or between many of the objects neighbourhood parcels. While 3D topological structures have been defined, they have not fully compliant to standards such as the LADM. The LADM not only provides a conceptual description of a land administration system, but also provides a 3D topology spatial profile. LADM also stipulates that geometrical information along with an associated topological primitive help to describe 3D spatial units.

LADM volumes can be bounded or unbounded at the top or bottom which is a reflection of real-world situations where there may be limited or unlimited rights or restrictions on the ground or skyward direction of a volumetric property. Various methods and characteristics of constructing 3D spatial units using LADM 3D topological model have been discussed in this paper in the context of a LADM specific topological model since a single model is not suitable for all types of applications. The approach based on the Tetrahedral Network (TEN) model is a suitable 3D topological model for volumetric parcels and is proposed as an alternative to boundary representation. Two fundamental considerations are that real-world phenomena have a volumetric shape, and can be considered a volumetric partition assist in modelling of 3D space. All elements of a TEN are convex and are well-defined allowing easy validation, analytical capabilities and integration with topography and other 3D data. TEN can be stored as explicit tetrahedrons or as vertices and the star or edges. Another method is to construct and perform topological validations of 3D cadastral objects on the fly based on boundary 3D face information. This can create both manifold and non-manifold solids and can model real-world cadastral features and legal spaces. The validation requirements for volumes are reduced and rely on the algorithm to create the volume using 3D faces and stored references. Finally, another approach is to use 2D topological features with stored height values, which is then used to

construct and validate 3D topological features. This approach can save storage space but is not totally viable for a 3D cadastre.
A section has been devoted to discuss the current software available to link current spatial DBMS possibilities to functional requirements and to focus on implementation and application. Developments were observed in the SDBMS domain where more spatial data types, functions and indexing mechanisms were supported. Two available SDBMS, Oracle Spatial and PostGIS were analysed in detail, while other SDBMS such as Microsoft SQL Server, MySQL have been seen to follow Simple Feature Access international standard. Most of these software including ESRI support 2D topology very well, however 3D topology is not supported natively yet. Comparison of various SDBMS for storing, and representing large point clouds was done with various software excelling in some aspects. ESRI's TIN structure, Oracle Spatial providing suitable data structure and mechanisms, MonetDB's in-memory perspective rather than a buffer perspective and ability to move data between storage hierarchies, Oracle Exadata's flat table model for data loading and querying and handling large number of points are some of the features of the current SBDMs.
A discussion on recent development of spatial databases follows with discussion on nD-array DBMS, comparison between file-based solutions vs. nD-array DBMS, and the development of modern Graphics Processing Units (GPUs) and their use in massive parallel architectures for processing large-scale geospatial data. In conclusion, the paper proposes a 3D topology model based on TEN synchronised with LADM specifications and the development of conceptual and physical model seems to be suitable for 3D cadastre and 3D registration. This topological model would utilise surveying boundaries to generate 3D cadastral objects with consistent topology and rapid query and management. Definitions for the validation of 3D solids should also consider the automatic repair of invalid solids. Point cloud and TIN related data structures available in SDBMSs should enable storage of non-spatial attributes such that database updates would store all relevant information directly inside the spatial database.

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Chapter 5. Visualization and New Opportunities

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Key words: 3D Cadastral Visualization, Users, User Requirements, Usability, Modelling, Presenting Information, 3D Environments, Interaction

SUMMARY

This paper reviews the opportunities offered by 3D visualization to improve the understanding and the analysis of cadastre data. It first introduces the rationale of having 3D visualization functionalities in the context of cadastre applications. Second, the publication outlines some basic concepts in 3D visualization. This section specially adopts the visualization pipeline as a driven classification schema to understand the steps leading to 3D visualization. It also includes a brief review of current 3D standards and technologies. A summary of recent progress in 3D cadastral visualization is then proposed, with use requirements, data and semiotics, and platforms are highlighted as main actions performed in the development of 3D cadastre visualization. This review is a first attempt at structuring and emphasising best practices in the domain of 3D cadastre visualization and it provides an inventory of issues that still need to be addressed. Finally, by providing a review on advances and trends in 3D visualization, the paper initiates a discussion and a critical analysis on the benefit of applying these new developments to the cadastral domain. This final section discusses enhancing 3D techniques such as dynamic transparency and cutaway, 3D generalization, 3D visibility modelling, 3D annotation, 3D data and web platforms, augmented reality, immersive virtual environments, 3D gaming, interaction techniques and time.

1. INTRODUCTION

In general, 3D cadastre is perceived as helpful for overlapping situations when property units vertically stretch over or cover one part of the land parcel as condominium with co-ownership, infrastructure above and below the ground as utilities network like cables and pipes or tunnels and metro. Visualization is a fundamental component of any cadastral system, providing instant clarity about the boundary of the land or any kind of property unit, such as a co-ownership right, mining right or marine right that cannot be achieved via a textual description (Lemmens 2010; Williamson et al. 2010). A particular benefit of 3D cadastral systems is that they offer better visualization support for complex multi-level properties.

Traditionally, cadastral visualization refers to the visualization of ownership boundaries on 2D maps and/or to descriptive data such as official measurements (length, azimuth, area, and owner's name) or legal documents such as title, deed or mortgage. For example, figure 1 illustrates Quebec cadastre plan with an example of 2D plan and a vertical profile to represent the overlapping situation of condominium units. While interaction with a 2D map may be possible (via geo-technology), the vertical or other profiles are mainly fixed, pre-defined when the cadastral system is created, and can only partially represent the increasingly complex 3D ownership and rights situations that are arising from increasing urbanisation. Adding an interactive 3D visualization system, which enables the visualization of the third geometric dimension in a flexible manner, allows users to explore the complexity of the 3D situation and gives the sensation of depth may certainly overcome some of the issues of 2D techniques or fixed vertical profiles.

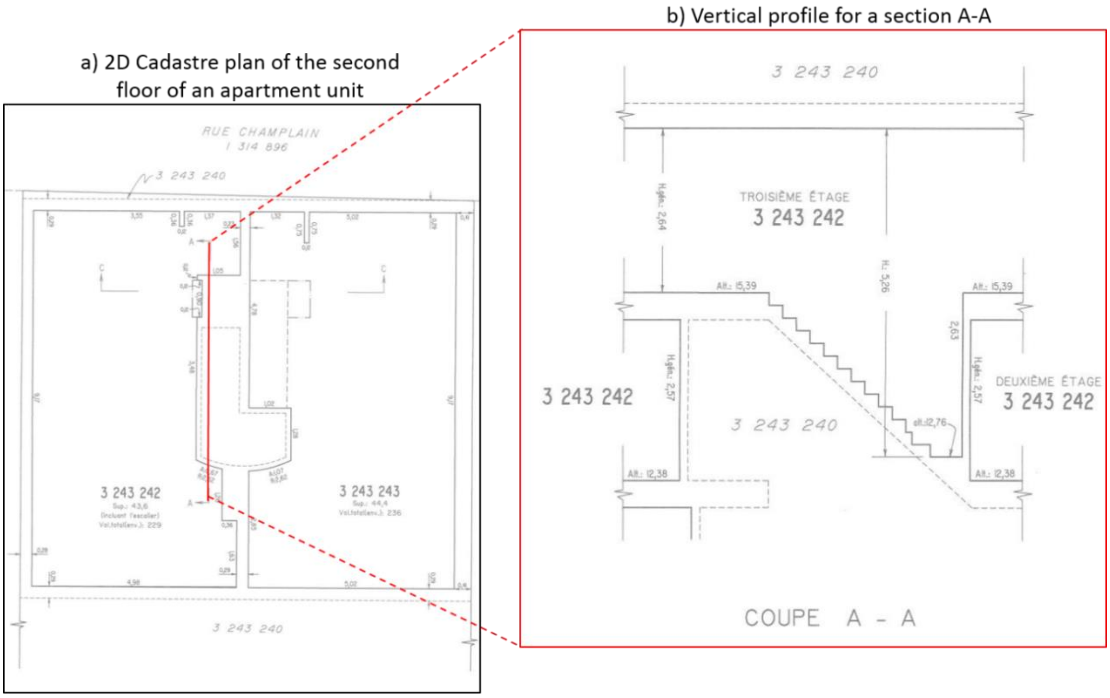


Figure 1. Example of vertical profile (Section A-A) used to represent the vertical dimension in the Quebec cadastre system (extracted from Infolot-MERN[1])

[1] Infolot is the online system for Land Register and Cadastre plan managed by MERN (Quebec Ministry of Energy and Natural resources).

Accordingly, having 3D cadastre visualization brings new opportunities including (Paasch et al. 2016; Rajabifard et al. 2014; Stoter 2004; Stoter and van Oosterom 2006):

- Improve understanding in 3D situations (3D spatial relationships, overlapping, conflict)
- Allow the visualization of an integrated 3D space of property units (above and below the ground)
- Increase information for the user, as additional data variables (height, Z, depth)
- Allow having access to 3D measures and slicing planes
- Provide a familiar view of the world (more realistic) and thus reduce misinterpretation
- Increase the level of interaction

Meanwhile, the third dimension for cadastral visualization results in new challenges as well (Shojaei 2014; van Oosterom 2013; Wang 2015):

- It may requires the user to have certain proficiencies of using 3D visualization interface in order to carry out cadastre related work properly.
- Standards, well-known mapping rules applied in 2D (e.g. selecting colour schema or symbols to represent the cadastre unit) may not convey the same meaning in 3D visualization.
- The occlusion (inability to see 'behind') in 3D visualization may be an obstacle for user perception of property units in a complex building. Some options:
    - Pre-select some 3D parcels for further exploration (using different levels of transparency), and others to provide context (making these more transparent, or even using wireframe display to distinguish them from the selected parcels),
    - Use exploding-views around selected parcels to allow users to examine in-details,
    - Allow the user to temporarily move objects to other locations (slide out a complete floor of building, and look inside), or
    - Slicing (horizontal, vertical, diagonal).
- Adding some reference topographic objects (buildings, roads, pipelines) and especially the earth surface, could be helpful but further complicates the visualization - – the more features and complexity the more cognitive load, and the slower system performance. Note that topographic objects can be in vector representation (polyhedral surfaces) or smart point clouds, and the same is true for the earth surface.
- From a static 3D image it may not clear if a 3D parcel (related to legal space of pipeline or building) is above or below the earth surface (and how deep or how high). Interaction may help, but it may also be helpful to include other visualization clues; e.g. connect via vertical sticks to earth surface.
- With regards to scale variation (perspective effect in 3D), the traditional visual interactions or usages with the cadastre data may be more complex to perform like locating a specific unit, taking 3D measurement or applying spatial operators as calculating the distance between two property units. Also in the case of non-regular (grid-like) objects, it may be difficult to estimate actual size and distances (compared to 2D map with a homogenous scale).
- Displaying partly unbounded objects (open at bottom or top side), with their infinite boundary faces while still maintaining the user's correct understanding of RRR, is very difficult, but is also a requirement within certain national cadastral systems.

- Visualizing 3D parcels and their temporal dimension (via animations or other techniques): either slowly changing parcels (continuously boundaries, e.g. near cost or river) or fast/ discrete changes (split of 3D parcel).
- Visually distinguish the legal objects with the physical objects in 3D, especially under overlapping scenarios.
- Availability of 3D cadastral data, and related data processing suitable for 3D visualization.

The purpose of this publication is to promote opportunities offered by 3D cadastres, with a specific focus on the role of 3D visualization as a routine communication tool. This publication may also be seen as a road map to conduct research and development in 3D cadastre visualization. This manuscript is an extended version of the paper published at the 5th International FIG 3D Cadastre Workshop (Pouliot et al. 2016). It first proposes an introduction to theories and concepts in 3D visualization. Second, a summary of progress made in the last years in 3D cadastral visualization is highlighted. Finally, by providing a review on advances and trends in 3D visualization, the paper initiates a discussion and a critical analysis on the benefit of applying these new developments to cadastre domain.

2. 3D VISUALIZATION

This section of the document provides some background theory in order to supply further detail about the challenges arising from 3D visualization. In particular, the illustration of the visualization pipeline highlights the number of stages through which data must be processed before appearing on screen. This can in turn result in slower performance should the datasets to be processed be large or the hardware on which the visualization is taking place be lower in specification. How the data is stored - i.e. its representation on disk - is also important as format conversion may be required before the data can be passed into the visualization pipeline.

2.1 Theory and concepts

The main aim of visualization - whether 2D or 3D - is to take representations of the real world and display them to a user, most frequently on a 2D screen (laptop, desktop computer, tablet). Visualization is known as to geovisualization when geographic phenomena is under study as it is for cadastral information (ICA 2015; MacEachren and Kraak 2001). Geovisualization presents a number of fundamental challenges - firstly, the real world coordinates stored within the data (i.e. its coordinate reference system, which refers to an origin on the surface of the earth) need to be translated to screen coordinates, where the origin is at the top left of the screen. Similarly, the real world distances - miles, meters - need to be scaled down to screen distances. Additionally, the real 3D world needs to be transformed into a 2D representation on the screen - even if the data is 3D, the screen itself is most of the time 2D.

3D visualization brings the z dimension[2] in the visual field as perception of depth (Dykes et al. 2005; Kraak 1988). There exist many approaches to produce depth perception as physiological cues like eye convergence, binocular disparity or motion parallax and psychological cues like retinal image size, perspective or shadows and technologies take advantage of them (Okoshi 1976). Formalizing the challenges outlined in the previous paragraph, the 3D visualization

[2] Note that in this case the z dimension is distance away from the eyes.

pipeline, as shown in figure 2, can be used to better understand the general processes that lead to 3D visualization (Chi 2000; Haber and McNabb 1990; Voigt and Polowinski, 2011; Wang 2015; Ware 2012). To illustrate these categories of product, figure 3 shows simple example of each step applied for representing the same building in 3D.
As can be seen in figure 2, the first stage of the process is data acquisition, which follows traditional routes in Geomatics including LiDAR, laser scanning or photogrammetry. Modelling, a part of the data acquisition process, consists in selecting which objects from the reality or data will be included in the model and in designing geometric and semantic (attribute) features and data structures to be used in order to store the model; in other words the mathematical representation (Marsh 2004; Requicha 1980; Turner 1992). Filtering and data manipulation to enhance or adapt the data as interpolation may also be required in the process of modelling. Mapping indicates the selection and interaction of visual variables and symbols to be applied to the 3D model in order to produce suitable 3D Map.It relies on semiotics; the study of signs and symbols as part of meaningful communication (Ware 2012). Some key foundations in mapping are those proposed by cartographers (Bertin 1983; MacEachren 1995), the principles of Gestalt or Tufte (Koffka 1999; Tufte 1992) or the information visualization (Ware 2012). The exact list of visual variables may vary from one author to another but it usually includes colour (hue and saturation), size, shape, orientation, value and texture.

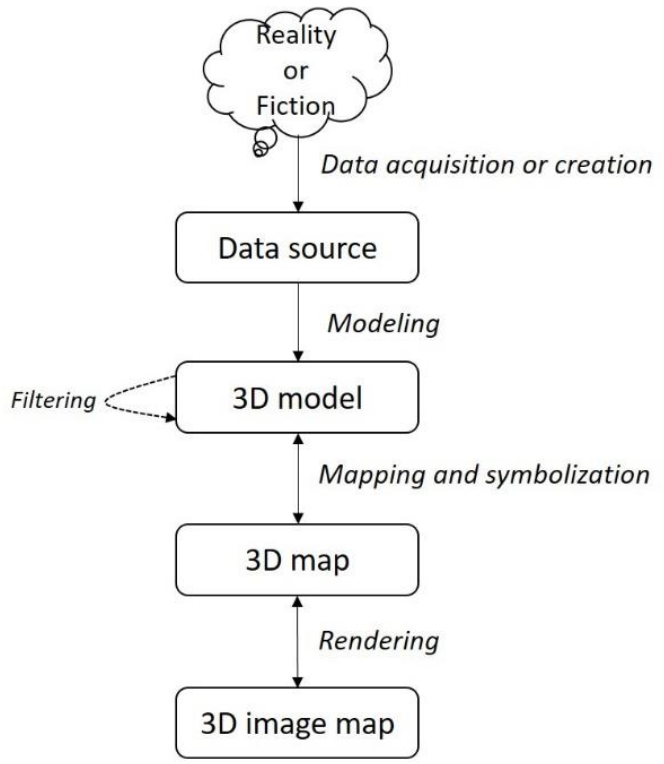


Figure 2. Visualization pipeline (adapted from Häberling et al. 2008; Semo et al. 2015; Terribilini 1999)

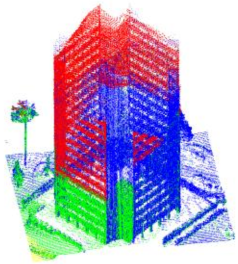
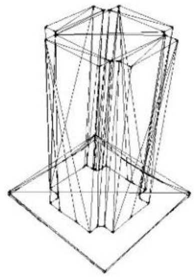
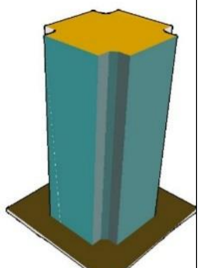
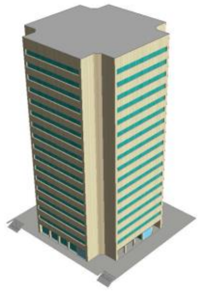
Image of reality	Lidar data source (coloured point cloud)	3D model (wireframe)	3D map (with colour code)	3D image map (with material)
				

Figure 3. Example of outputs corresponding to each stage of the visualization pipeline in figure 2 (the model represents one campus building at Université Laval, Canada)

Graphic rendering follows on from mapping. Rendering is the process of generating images from the geometric models and data and it involves many processes as how light is applied (direction, shading, reflection), rasterization, varying the viewpoint, applying texture and transparency, adding effects as atmospheric condition, seasonal variance (Marsh 2004). Rendering may be non-photorealistic rendering or photorealistic which consequently enable more realistic views. Rendering techniques also allow the production of animated images, and thus create the notion of moving objects.

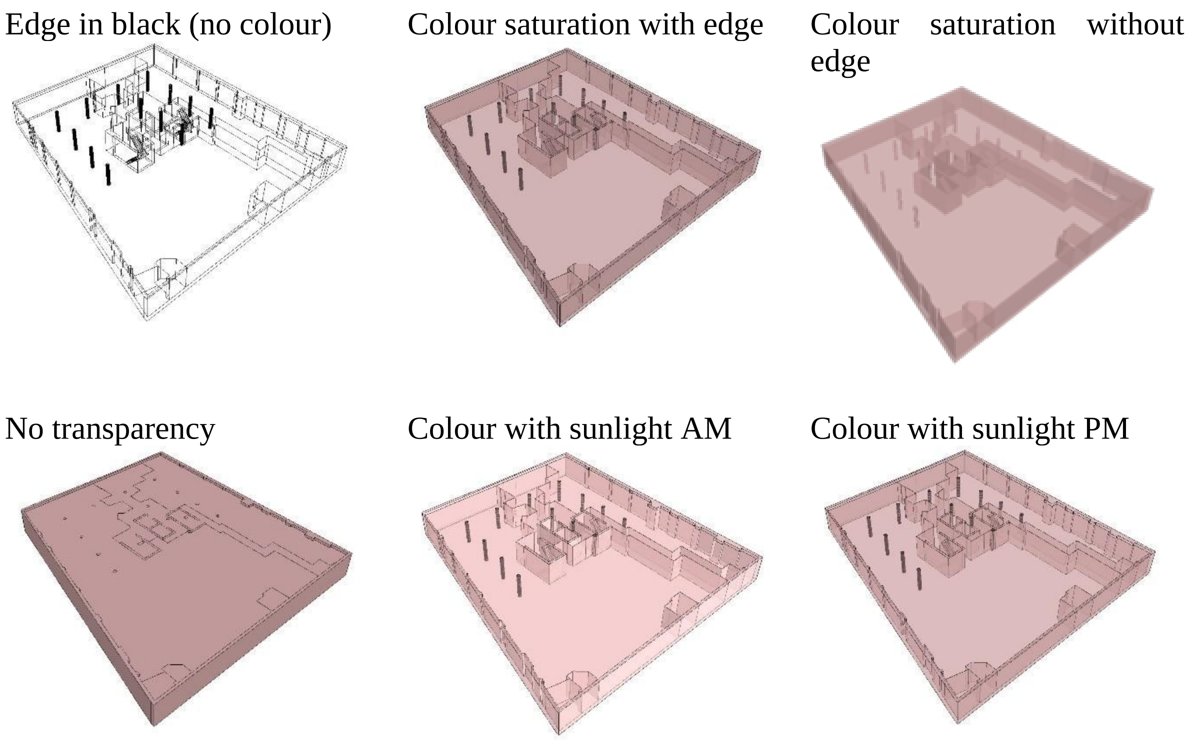


Figure 4. Examples of visual impact when modifying rendering and mapping parameters for 3D visualization (original 3D model built by group VRSB, Quebec City)

Figure 4 shows one floor of an apartment unit with stairs in the middle (no ceiling or floor are represented) for which rendering and mapping parameters are modified to illustrate the impact on the 3D visualization schema. As it can be seen, modifying mapping and rendering parameters may greatly affect our capacity to see, select or distinguish objects and thus taking decision based on it. Research into 3D visualization may occur in any of the phases of the visualization pipeline but typically, advances in visualization target the aspects of mapping and rendering. This paper does not address various aspects of the acquisition and modelling phases.
In addition to the concepts presented in figure 2, interaction, the dialogue between a human and a map mediated through a computing device (Roth 2011) also happens in the visualization process. Interaction may occur in changing the rendering parameters, focusing, arranging the symbols, etc. The ability to select, and therefore interact with, objects in a 3D environment is fundamental to the success of any 3D system (Bowman et al. 2012). The same applies to human related phenomena as perception (psychological and physiological facets), memories in vision, cognitive science since they all may impact the designing and the usage of visualization system (Miller 1956; Popelka and Dolez 2015; Ware and Plumlee 2005).

2.2 Representations and Standards for Storage and Data Exchange

In order to be used for visualization, the data captured at the start of the above pipeline must be stored in a format appropriate for downstream use. In this chapter, the term "D" refers to the geometric dimension and any 3D visualization will require having 3D geometric information, either as a Z coordinate, height or depth information attached to the geometric objects like vector geometry as point, line, surface or solid or volume element (voxel). It should be noted that while this Z information is required for any 3D visualization, solid objects or voxels are not a necessity. For example, a 3D model may be produced from the assembling of surfaces, often called boundary representation (Requicha, 1980). To illustrate this aspect, figure 5 presents 3D visualization of various categories of 3D data in the context of geological modelling (Bédard 2006). Pertinent standards in 3D visualization relate to both data format and grammar, implementation as with programming interfaces (API) and Web Feature Services. Many of them are proposed by ISO, OGC and W3C. For instance, CityGML acts as an open standardised GML[3] data model for 3D city models and it proposes formalization for the model appearance (Gröger and Plümer 2012; Kolbe et al, 2009; OGC 2012) as well as its content (i.e. what features are modelled and to what accuracy). The Industry Foundation Classes (IFC), built and maintained by buildingSMART and adopted by ISO-16739, is a specification largely in used in the context of Building-information modelling (BIM). BIM-based approach provides significant benefits for visual communication of properties, particularly in complex urban built environments, with both IFC and CityGML focusing on 'intelligent' visualization – i.e. geometry with associated attributes (Atazadeh et al., 2017a,b). Other 3D formats that focus purely on geometry without specifying content include X3D, OBJ or KMZ produced by Google Earth. COLLADA (COLLAborative Design Activity) offers an interchange file format. WebGL is a Javascript API for 3D graphics on the web that provides an interface to the 3D graphics hardware on a machine (Parisi 2012). It has emerged as the programming language for 3D graphics on the web, allowing a fully customized 3D software package to be developed (Evans et al. 2014). Finally, OGC is also working on 3D Portrayal Services that enable visualization (OGC 3D Portrayal 2012).

[3] Geography Markup Language.

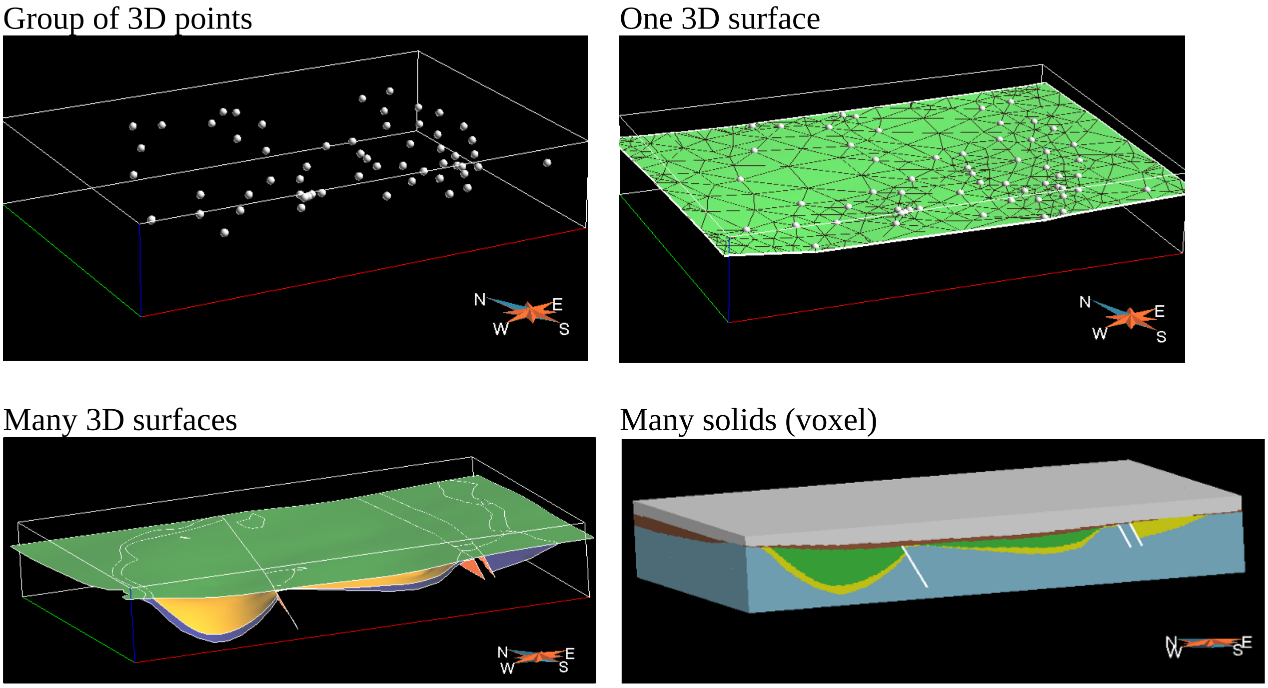


Figure 5 3D visualization of 3D data representing geological features (3D models built by Bédard 2006 with Gocad)

2.3 Generic Technology and Software

Two categories of 3D visualization device can commonly be identified - monoscopic 2D display screens and stereoscopic 3D devices that mimic the human vision thanks to 3D glasses or stereoscopes (sometime called True 3D visualization). On 2D screens, to reproduce the third dimension and give the illusion of depth, we usually apply projection techniques (Marsh 2004; Foley et al. 2003). The projected image could be calculated based on plane, sphere or cylinder form. Planimetric projection is the most common technique in use and two categories are typically found in computer software: perspective and parallel projections, with the perspective view dominating. Increasingly stereoscopic 3D visualization systems can be supplied on local platform, on Web or mobile devices. 3D visualization can also be performed with room-size immersive visualization (virtual reality) environment such as that provided by a 3D CAVE (Philips et al. 2015).

Software tools offering 3D visualization capabilities are abundant and can broadly be divided into graphics and game tools (e.g. *Blender*, *Google Sketchup, Unity3D),* computer assisted design (e.g. *Bentley Microstation*, *Autodesk Autocad*), geographic information systems (e.g. *ESRI ArcGIS* or *CityEngine*, *QGis*) or 3D Viewers (e.g. *Adobe 3D PDF*, *Google Earth*, *ParaView*). An additional categorisation divides the group of tools into those that offer data handling and modelling capabilities or 3D viewers, which are dedicated to 3D visualization (without editing options). An example of the latter is the well-known Adobe Acrobat format, which also proposes an option for 3D PDF file handling and offers minimal options to modify colour, transparency, projection and navigation. Google also proposes a 3D globe (Google Earth) which includes the visualization of 3D buildings for some cities in the world.

2.4 Comparing 2D and 3D Visualization

As it can be seen, addressing 3D visualization challenges requires knowledge and expertise from various disciplines and is a double-edged sword: it opens new possibilities, but also brings in new issues. Bleisch and Dykes (2015), Savage et al. (2004) or St-John et al. (2001) have presented comparative analysis in 2D and 3D visualization on how effectively and efficiently spatial data can be visually analysed in relation to specific tasks. While best practice for efficient mapping in 3D should be the same as it is in 2D, this is not the case - 3D visualization brings additional challenges when compared to 2D including: (Elmqvist and Tsigas 2008; Hardisty 2003; Jobst and Döllner 2008; Shepherd 2008; Todd 2004; Tory et al, 2006) :

- Occlusion and shadow management
- Orientation and position perception
- User interaction and experiences
- Photo Realistic option (more realistic views)
- Scale variation (perspective effect) and orientation dependency when measuring
- Depth perception

3. CADASTRAL SYSTEMS AND 3D VISUALIZATION

Although it is still an emerging field, some literature on 3D cadastre visualization exists and the topic was specifically addressed during the five 3D cadastre workshops (Fendel 2002; Pouliot 2011; Banut 2011; Pouliot and Wang 2014; Pouliot and Ellul 2014). On a total of 137 papers published during these workshops, and although many of them propose 3D pictures of cadastre, less than 15 papers focused on the 3D visualization aspects of cadastral data. The group discussion and material published during these 3D cadastre workshops and complementary literature review in scientific journals underpin this analysis. Three sections are proposed to synthesis the current activities in 3D cadastre visualization: user needs, data and semiotics/rendering aspects and visualization platforms.

3.1 Users and User Requirements

During the workshops, there were a number of discussions relating to users and their needs and researchers show an increasing understanding that users must be part of development and research activities for cadastral 3D visualization (Pouliot et al. 2014; Shojaei et al. 2013; Shojaei 2014; Stoter et al. 2013; Wang et al. 2016). A number of studies in this area are considered here, and overall the review shows that users are still eager to learn about the specific advantages of using 3D visualization.
Looking in more detail, the review indicates that cadastres' **users** are mainly the user groups who would also make use of 2D cadastral systems - i.e. managers in government and municipal authorities responsible for the maintenance of the land administration system, as well as lawyers and notaries, land surveyors. The third dimension in cadastre system also appears to contribute of having (or increase) opportunities for new users of cadastre data, including architects, engineers, developers, real estate agents (Atazadeh et al. 2017). Architects and engineering for example already use 3D models for their own obligations and thus may be used to interacting with data in this manner; having 3D cadastre integrated or available is perceived as valuable. Another example to mention is marine areas, 3D visualization is offering many advantages and cadastre information (property/tenure) is part of it (Athanasiou et al. 2016).

Additionally, a questionnaire addressed to Quebec municipalities compared user expectation regarding cadastre data in 2D and in 3D and showed that overall, the cadastre related tasks are mainly the same in 2D and 3D (Boubehrezh 2014). In brief, interacting with3D visualization of cadastral data appears helpful to (Boubehrezh 2014; Pouliot and Boubehrezh 2013; Pouliot et al. 2014; Shojaei 2014; Shojaei et al. 2013; Wang 2015):

- Identify and understand the 3D geometric boundary of the property units.
- Locate a specific 3D property unit.
- Look inside and outside the boundary of the 3D property unit.
- Find adjacent objects of a 3D legal object, both vertically and horizontally to identify affected RRRs (Right, Responsibility, and Restriction).
- Distinguish the boundaries of the 3D property units and the associated building parts.
- Distinguish the private and common parts in 3D co-ownership apartment buildings.
- Identify volumes that are to be merged or subdivided and thus facilitate the registration process.
- Trace utility networks and infrastructures (e.g. tunnel and bridges) and control the proximity with ownerships boundaries, and detect collisions.
- Visually check the spatial validity and data quality, e.g. volume is closed, no overlap between neighboring volumes, and no unwanted 3D gaps.
- Examine the property units in the context of their 3D surrounding environment.
- Associate public and building elements with 2D land parcels and compare their 3D geometry and spatial relationships.
- Perform 3D measurements such as calculating the surface area or volume of the property.
- Perform 3D geometric analysis such as 3D buffering, e.g. in the case of easement applications.
- Analyse3D spatial relationships such as 3D overlapping analysis to identify RRR conflicts.
- Support other management systems including the co-visualization with land taxation, construction permits, urban planning, and land use regulation.

Table 1. Users and User Requirements of 3D cadastre system visualization

User types	Requirements	Challenges
- General Public - Land Registry - Local Governments - Land surveyors, Notaries, Land lawyers - Architects, Engineering and Construction - Land and urban planners - Property development - Building Management - Real Estate	- Identify 3D property - Understand the 3D geometry - Locate and compare - Measure and perform spatial analysis - Control accuracy - Query geometry and attributes - Interact with - Integrate with other applications	- Steep learning curve - Presenting a solid value proposition - Barriers to legal and institutional adoption - 3D visualization for other applications - Multipurpose cadastral systems

To those 3D cadastre interests, we may also add the traditional functionality available in 3D visualization systems, such as zoom in-out, pan, having tooltips, or mapping and rendering controls (as changing the colour, the type of symbol, the level of transparency, the shadow effect, etc).

In terms of **usability**, while advanced systems such as *ESRI CityEngine* do exist to facilitate 3D visualization, the steepness of the learning curve required to operate them perhaps makes them unsuitable for many of the user groups identified during the various workshops, both technical experts and members of the public (Ribeiro et al. 2014).

To summarise this section, the table 1 recaps the user types, user requirements and current gaps identified in literature in regards of 3D cadastre system visualization.

3.2 Information to Visualize and Semiotic/Rendering Aspects

Discussions on what to represent (information) and how (semiotic and rendering aspects, i.e. the best way to communicate information) in 3D visualization were also featured throughout during the 3D cadastre workshops.

3.2.1 What to Represent

The need for full 3D (solid) representation has been considered at all workshops but as yet most of the current cadastre systems are still proposing 2D plans and limited 3D information, and for backwards compatibility any visualization systems would also have to allow a good visualization of 2D data. The Land Administration Domain Model (ISO-TC 19152-LADM, 2012) provides an exhaustive list of cadastral data and modelling aspects to consider. For example, a digital cadastral mapping system in a multipurpose environment may include the following core components (IAAO, 2015):

- geodetic control network based in a mathematical coordinate projection
- cadastral parcel layer delineating the boundaries of real property in the jurisdiction
- other cadastral layers related directly to the parcel layer, such as subdivision, lot and block, tract, and grant boundaries
- unique identifier assigned to each property
- attributes (semantic) to describe the geometry of the property as length, area, volume or to describe the RRR attached to the property as deeds, titles, easements
- computer system that links spatial data and registration system.

Given the wide variety of geometric and semantic objects in a 3D cadastral system, it is no surprise that a number of different groupings of data exist. While Isikdag et al. (2015) distinguish between physical and virtual objects, Aien et al. (2013), Shojaei et al. (2013, 2014), Pouliot (2011) and Wang (2015) suggest that at least two types of spatial objects are necessary for cadastral 3D visualization as the boundaries of physical objects and the boundaries of legal objects (the term administrative boundary may also be used). Besides, Döner et al. (2011), Guerrero et al. (2013), Guo et al. (2013), Jeong et al. (2012), Pouliot et al. (2015), Shojaei et al. (2013) and Vandysheva et al. (2012) propose the visualization of underground objects as part of cadastre systems.

The debate also includes a core focus on the importance of representing not only legal but also physical representation of the world, the need to distinguish between private and publicly owned land, the need to formalize the spatial relationships along with the potential to link additional information—e.g., official documents—to the 3D geometry. Mapping legal boundaries that do not physically exist poses a certain number of issues, and some solutions have emerged from research (Aien et al. 2013; Griffith-Charles et al. 2016; Shojaei et al. 2014). Most of these propositions suggest the visualization of orthophotography and legal boundaries draped on a 3D globe. As shown in figure 6 that presents the 3D visualization of bridge and legal boundaries of Shenzhen Bay port, the legal space is enlarged and distinct from the physical space of the construction (Guo et al. 2011). Only through the 3D visualization can we clarify the difference of these spaces.

Figure 6. Shenzhen Bay Port 3D visualization of bridge and legal boundaries (source Guo et al. 2011)

A legal boundary defined by the interior surface of walls

A legal boundary not defined by the physical structure

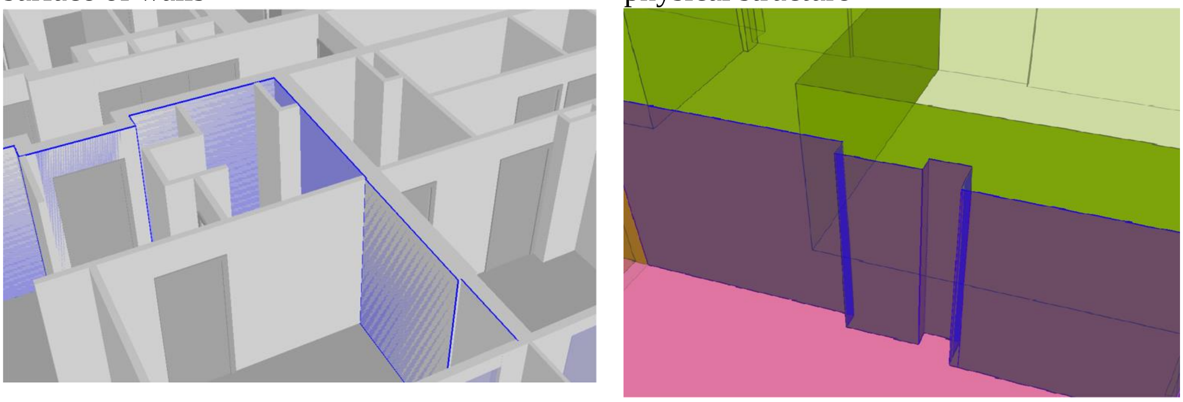


Figure 7. BIM distinction between legal and physical boundaries (built from Atazadeh et al. 2017)

Figure 7 shows another example that allows the visualization of inside building (Atazadeh et al. 2017). It was shown that the BIM environment can potentially be utilized to provide a more communicable method of representing a wide range of legal and physical boundaries defined in the state of Victoria in Australia. However, traditional BIM does not yet provide support for defining 3D legal objects (Atazadeh et al. 2017; Shojaei et al. 2014). Visualizing invisible or virtual objects like legal boundaries may be examined from the same research standpoint of underground objects, the visualization of which was, in turn, identified as a shortcoming of existing systems. Figure 8 shows 2D traditional view of superimposed buildings, cadastre parcels and underground networks, while the zoom offers a 3D view of the same objects.

Additionally, having access, and thus being able to visualize descriptive data as an attribute is also important for cadastral applications. Figure 9 from Atazadeh et al. (2016) shows an example of managing legal information associated with a private property in the 3D digital data environment of BIM.

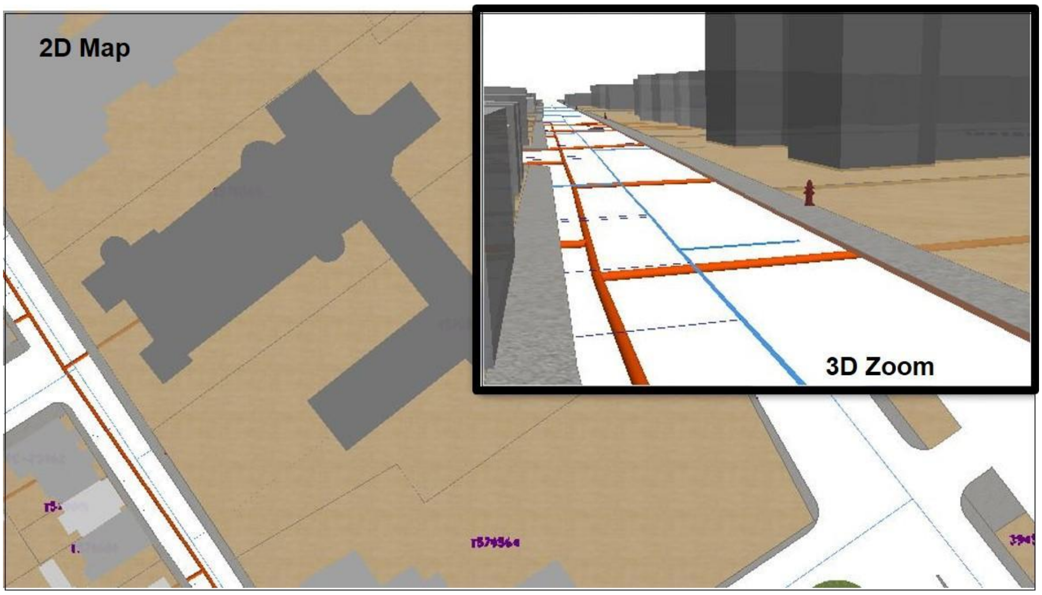


Figure 8. 3D Zoom of overlapping buildings, land parcels and underground networks

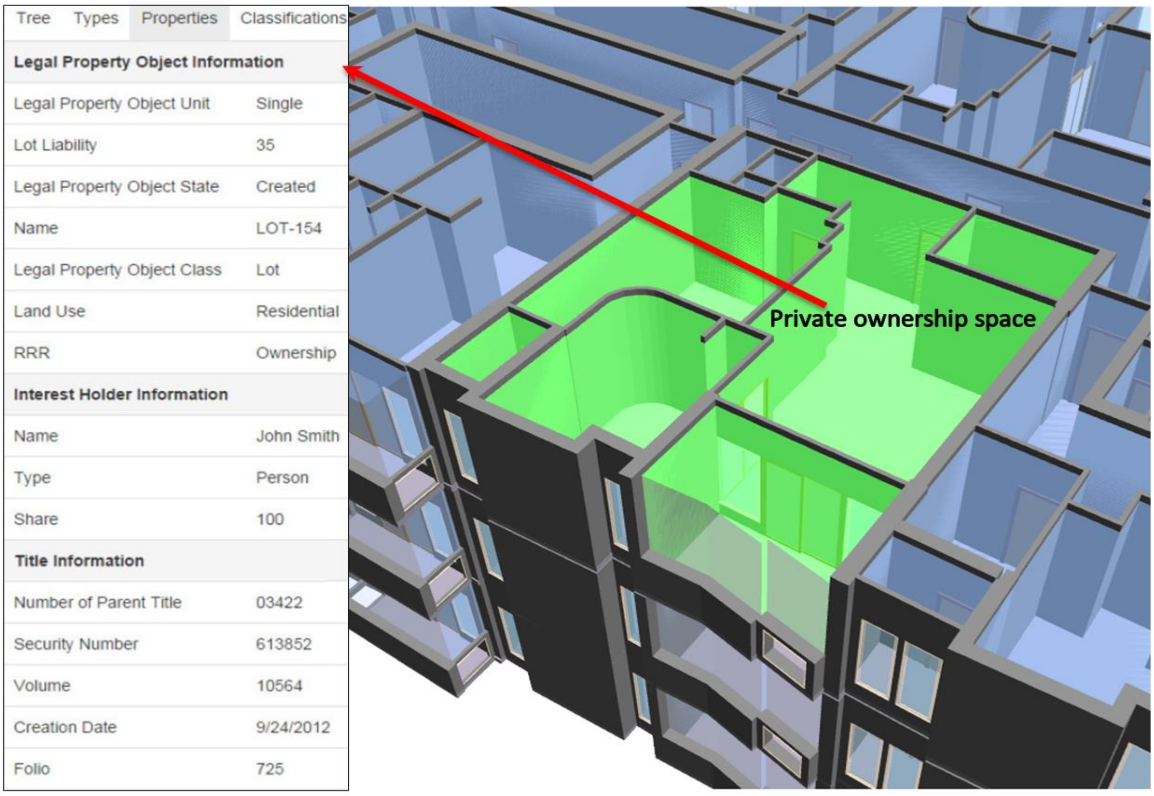
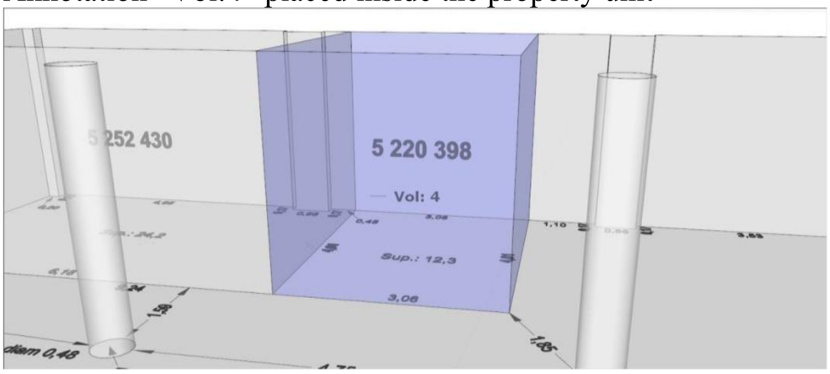


Figure 9. Representing and managing the legal (land administration) information in the BIM environment. On the left, a list of attributes of the private ownership space (built from Atazadeh et al. 2016)

One important outcome of the survey conducted by Pouliot and Boubehrezh (2013) is that users require 3D annotation (official measurements) marked on the 3D model. Wang (2015) and Pouliot et al. (2014) tested the suitability of having 3D cadastre annotation in face-to-face interview with notaries. They assess the 3D position of annotation (inside, outside, next to) for marking the volume of the property unit (figure 10 shows two examples) located in an apartment. Positioning the annotation outside the volume is identified by the notaries as not helpful to achieve this task. Finally, some authors argue that, to manage and consequently visualize information in a cadastral system, time (4D) should be part of the explicit data (Döner and Biyik 2013; Siejka et al. 2013; van Oosterom and Stoter 2010). Seifert et al. (2016) for example argue for the development of multidimensional cadastre system that includes information related to energy, noise protection, urban planning, disaster management and time-related cadastral information such as monitoring the development of cities over time, statistic of changes of land user/land cover or historical archiving. Having a 3D visualization system that allows integrated views of multiple sources of data, including cadastre, and animation scenarios appear as a major challenge.

Annotation “Vol:4” placed inside the property unit



Annotation “Vol:4” placed outside the property unit

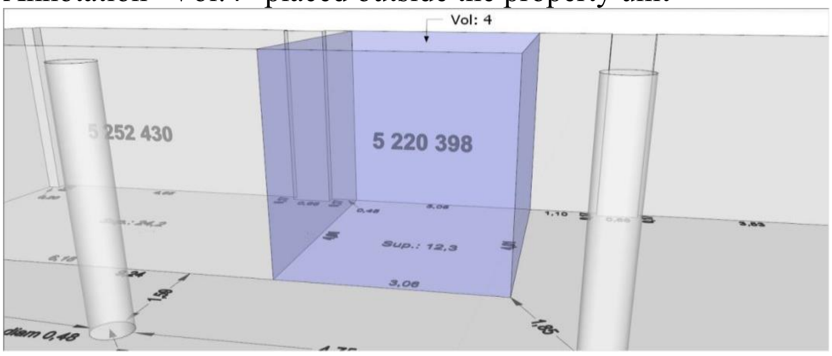


Figure 10 Varying the position of 3D annotation associated to the property unit 5 220 398 (original 3D model built by group VRSB, Quebec City)

3.2.2 Semiotics and Rendering

To date, very few researchers have addressed cadastre symbolization from a point of view of the semiotics of graphics. Wang (2015) and Pouliot et al. (2014) in their experiments with 3D cadastre visualization, evaluate the suitability of visual variables (colour hue, colour saturation, position, value, texture and transparency) against six notarial tasks[4]. In their results, with or without transparency, the colour (hue) is among the preferred visual solution compared to value and texture for selection purpose. Colour (saturation) performed well to allow the association of lots into two groups. Additionally, it is well recognized that transparency is a central technique in 3D visualization system and the same apply to 3D cadastre visualization. Ying et al. (2012) offer a good example in using transparency to depict the boundary difference between cadastral spaces and buildings spaces (figure 11).

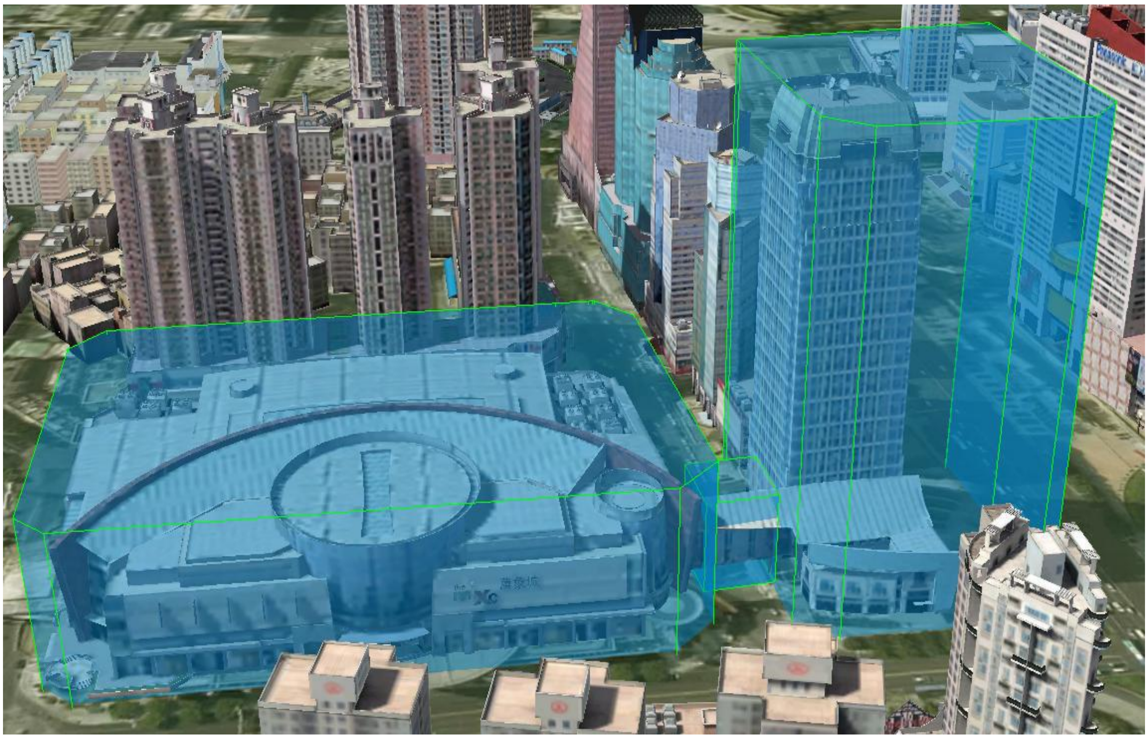


Figure 11. Using transparency to enhance the visualization of 3D cadastre and building spaces (source Ying et al. 2012)

Furthermore, Wang et al. (2016) explore transparency in 3D cadastral visualization, demonstrating that this is useful to help users delimit property units (administrative boundaries) by using their physical counterparts (e.g., walls). Figure 12 illustrates two examples of transparency levels tested during the experiment. They found that, in general, using three different transparency levels is preferable and efficient solution to help users demarcate property units with their physical counterparts. Applying very high transparency to simple legal boundaries as compared to simple physical boundaries improves user certainty in the decision process. Using higher transparency on the physical boundary (wall) is more effective in communicating to users the concept of ownership.

[4] 1) See the geometric limits of the 3D lots, 2) Characterize a specific 3D lot according to its official information, 3) Locate a specific 3D lot inside the building, 4) Distinguish the limits of the 3D lot and the associated building, 5) Distinguish the private and common parts of the condo, 6) Understand the neighbouring relationship between 3D lot and its surrounding lots.

High transparency used to illustrate the wall — Low transparency used to illustrate the wall

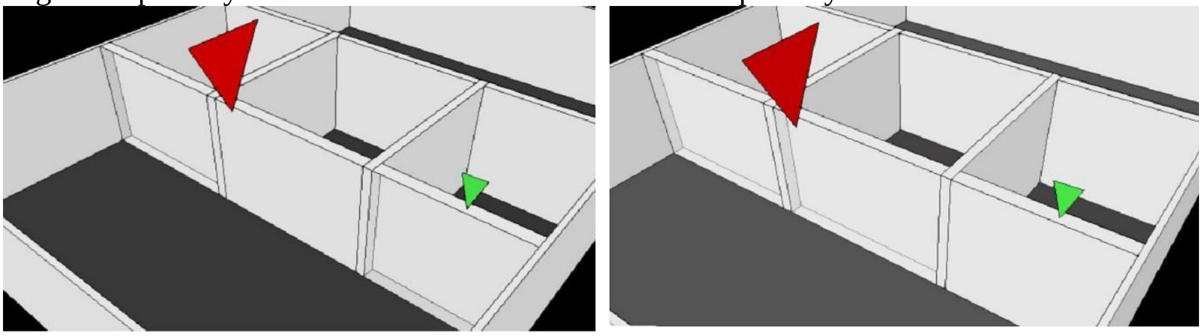


Figure 12. Testing transparency levels for ownership establishment. Participants had to decide whether this wall part belongs to the private property unit or not. The red arrow points to a private property unit and the green arrow points to a wall part (source Wang 2015)

Other researchers demonstrate highlighting techniques such as colour rectangles, detaching floors or slicing to improve the communication level (Pouliot et al. 2014; Shojaei 2014; Vandysheva et al 2012). For example, Ying et al. (2016) develop discretization and distortion of the set the property units (identified as coherent set) and depicted their relative spatial locations and spatial relationships (figure 13). An orthogonal function is used to discretize the coherent set of units and then displacement equations are applied while keeping the focus on one specific unit (the red one in figure 13). This distortion transformation and visualization effectively draw the inside property unit that cannot be visible in reality, only with the outer surfaces and appearances. Figure 14 illustrates another example of the use of slicing and detaching floors to get an inside view of the units.

The coherent set — The same set with distortion and focus

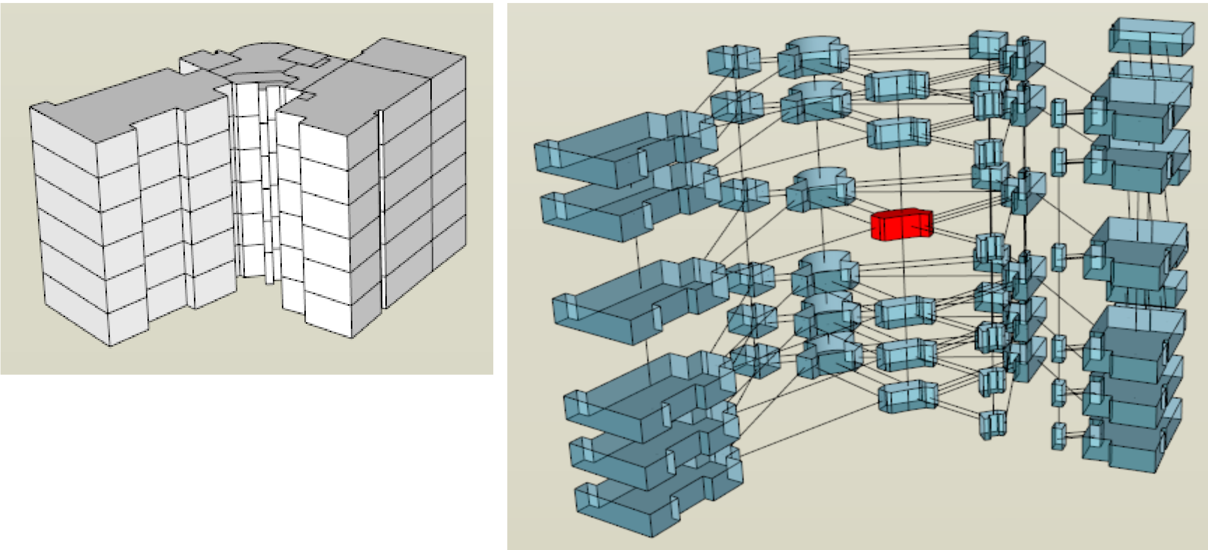


Figure 13. Distortion visualization of 3D property units (source Ying et al. 2016)

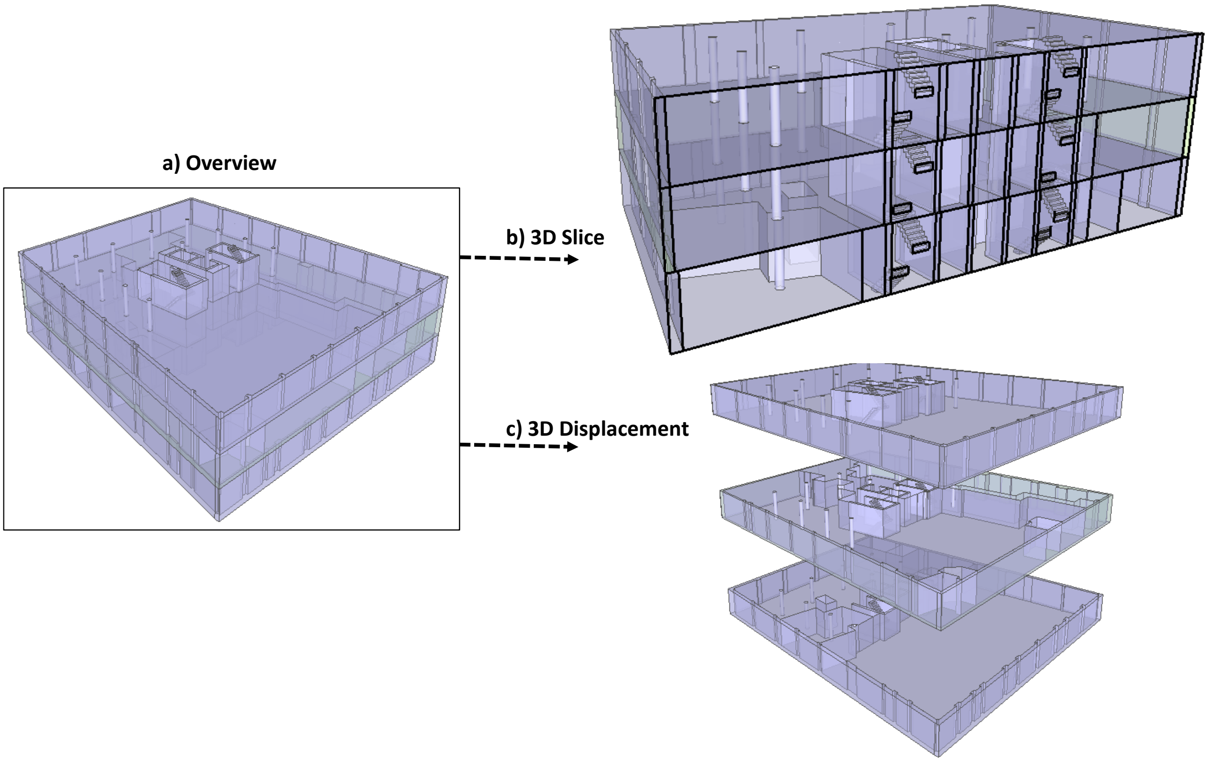


Figure 14. Highlighting techniques applied to the visualization of three floors of an apartment (original 3D model built by group VRSB, Quebec City)

Table 2 summarizes the current trends in 3D cadastre visualization regarding information and semiotic/rendering aspects and current gaps identified.

Table 2 Cadastral information and semiotic/rendering aspects of 3D cadastre visualization

Cadastral information to visualize	Semiotics and Rendering	Challenges
- Physical, legal and virtual objects/ spaces/boundaries as: • Annotations and attributes • Descriptive or legal documentation • Private and common parts • Private and publicly owned land - Spatial relationships - Time and "chain" of property right	- Altering and suitability of visual variables - Applying texture and transparency - Colour rectangle - Slicing, cross-sections - Discretization and distortion	- Legal boundary not visible - Embedding within the legal decision making process - Availability of 3D cadastre data - Geometric complexity of apartment - Temporal data visualization

3.3 Visualization Platforms

Alongside the generic platforms identified in *Section 2.3* above, emerging web-based technology as websites and web services were a clear focus in the review, which identified many prototypes built specifically for 3D cadastral systems that include web-based and desktop systems for which. Open-source solutions were identified as having particular relevance.

In the context of **web-based systems**, Shojaei et al. (2014) establish a web-based 3D cadastral visualization system with a comprehensive review of functional visualization requirements and the applicability of 3D visualization platforms. They also developed a 3D visualization system based on Google Earth for 3D ePlan/LandXML data to be used in overlapping property situations (Shojaei et al. 2012). Figure 15 shows some examples of the interface proposed by the prototype of 3D ePlan developed by Land Use Victorian Government. It is used to illustrate how the legal and physical objects of a building subdivision plan can be stored, visualised and queried in a 3D digital system (Olfat et al. 2016).

Aditya et al. (2011), for the jurisdiction of Indonesia, develop two 3D cadastre web map prototypes based on KML with Google Earth and X3D with ArcGIS online, respectively. Stoter et al. (2013) explain how in Netherlands 3D cadastre maybe applicable and in 2016 (Stoter et al. 2016); they present a first attempts to accomplish 3D cadastral registration within the existing cadastral and legal framework.

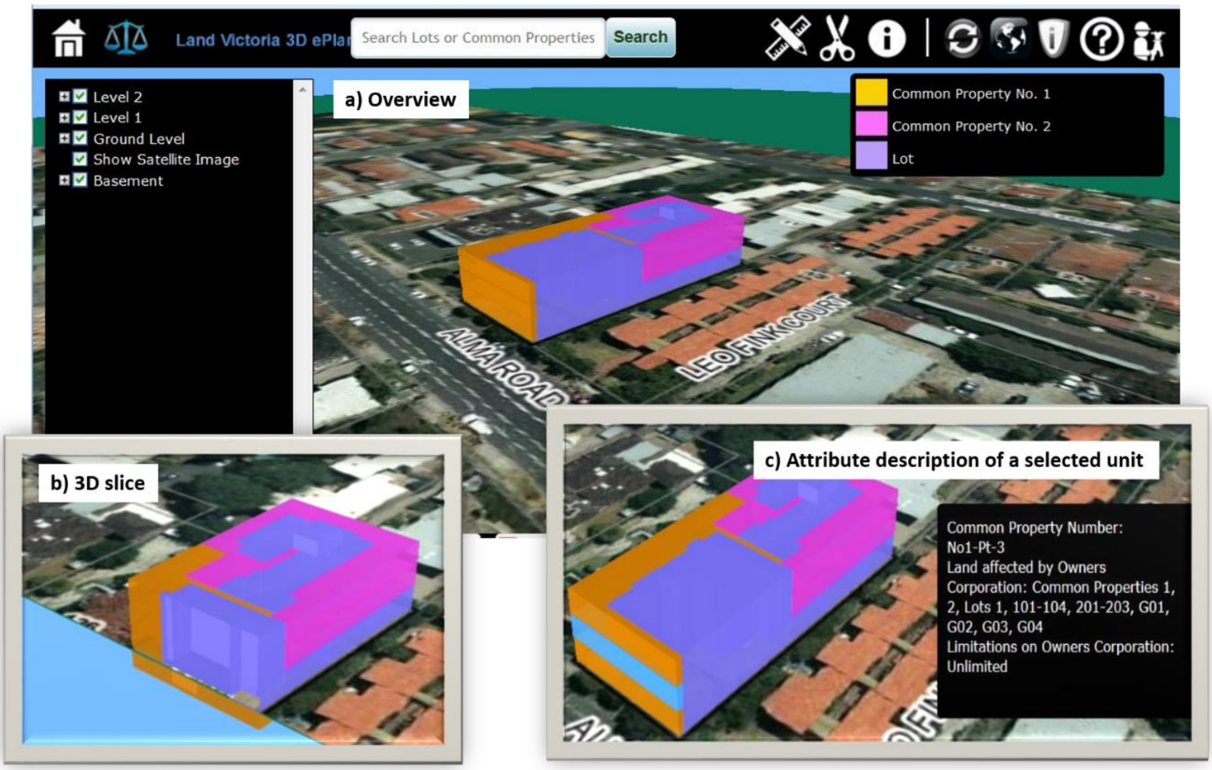


Figure 15. Land use Victoria prototype for online 3D ePlan (extracted from https://www.spear.land.vic.gov.au/spear/pages/eplan/3d-digital-cadastre/land-victoria-3d-eplan-prototype.shtml)

Additional visualizations were based on a **desktop** version of Google Earth. In China, Guo et al (2013) developed a 3D cadastre for the administration of urban land use for the city of Shenzhen. In Korea, Jeong et al. (2011) explored the future settle of 3D cadastre. Vandysheva

et al. (2012) presented a 3D cadastre prototype applicable in the Russian Federation. Vucic et al. (2016) assessed the possibility for upgrading Croatian cadastre to 3D. In the context of Spain, Oliveres Garcia et al. (2011) explained how to use KML and Google Earth to visualize a volumetric representation of property units in condominiums. As illustrated in figure 16, Ribeiro et al. (2014) tested ESRI CityEngine for use in Portugal 3D Cadastre visualization.
On the other hand, Shojaei (2014) exploited a stereo approach using 3D anaglyph glasses to present ownership rights. In this technique, two different images are presented into right and left eyes to give 3D perception (figure 17).

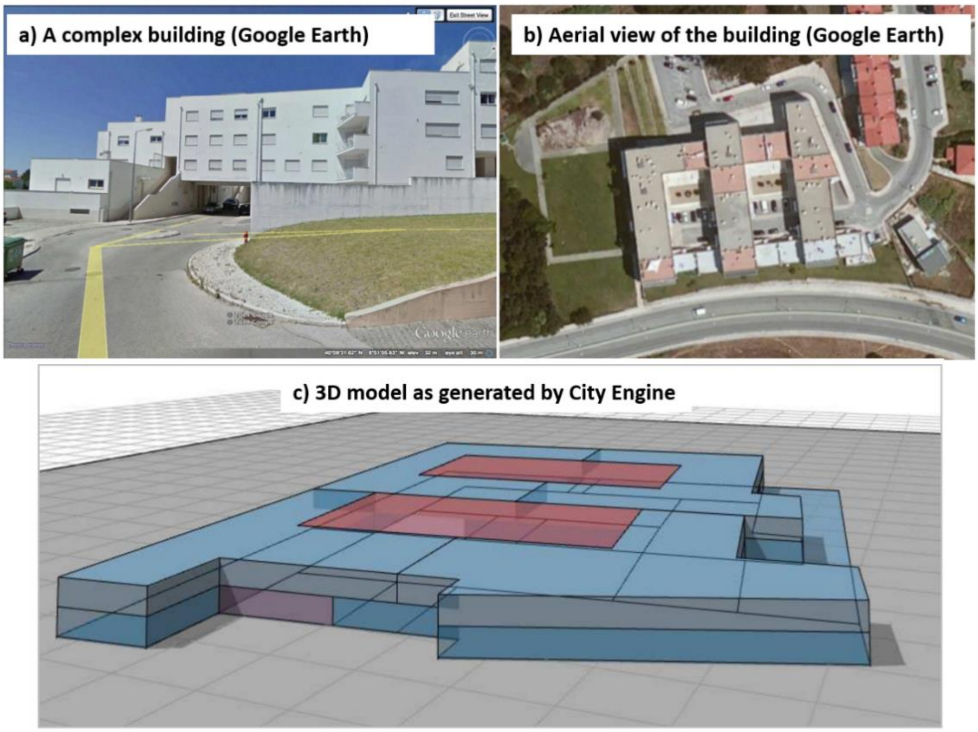
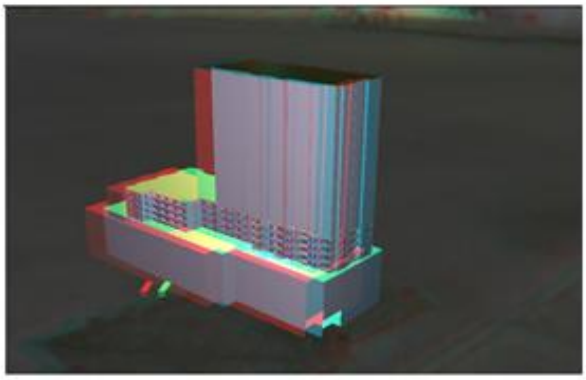


Figure 16. Generating 3D Cadastral Data using ESRI City Engine (source Ribeiro et al 2014)

A stereo representation of ownership rights



Presenting the prototype to the industry

Figure 17. A stereo representation of ownership rights based on anaglyph approach (source Shojaei 2014)

As noted in *Section 3.1*, the ability to select, and therefore interact with, objects in a 3D environment is fundamental to the success of any 3D system (Bowman et al. 2012). Visual highlighting techniques previously discussed are helpful to perform such interaction with the 3D model. In a Russian prototype (Vandysheva et al. 2012), users could drag out the 3D model of a floor together with the 2D plan of the entire building in order to overcome issues related to occlusion. In order to look inside a building, it was also possible that user interaction could be applied to temporary drag a floor with 3D parcels outside the building (figure 18). The benefit of interaction is that user is controlling this temporary distortion and therefore is not given an incorrect mental picture (and human intelligence is used to find a suitable location when dragging a floor outside the building).

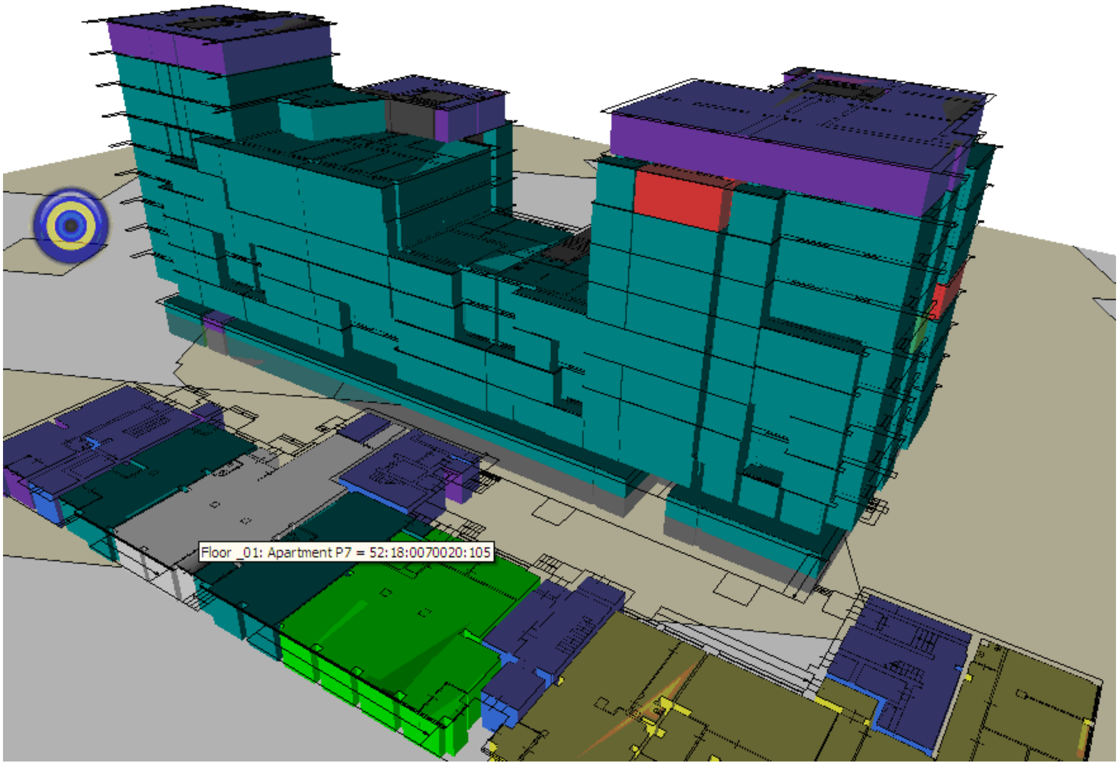


Figure 18 Floor_01 dragged outside the building. Note the tooltip which contains the identifier of the object during move-over (apartment P7). Source: (Vandysheva et al. 2012)

User interaction could also be used to switch on or off certain visualization clues. In a static image, it might be quite difficult to estimate the relative depth or height of objects. Toggling on/off vertical height/depth cue stick may help the user to get proper impression (in addition to moving, rotating, etc.); see figure 19.

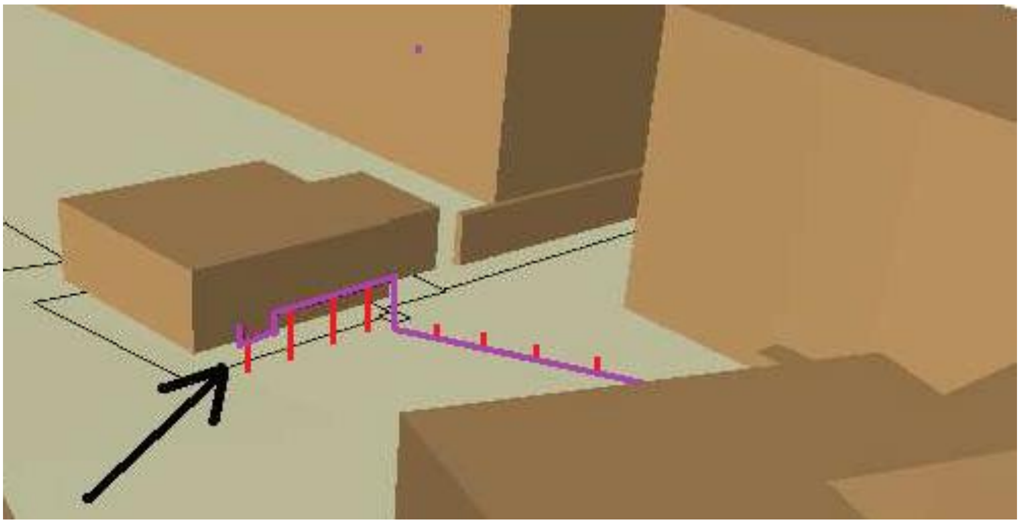


Figure 19. The pipeline (the purple line, starts above ground near arrow and is partly below ground). The black lines on the surface are the normal 2D parcel boundaries. The virtual 'red sticks' show vertical distance to surface, this is a clue for above/below the surface and the actual depth/height, and can be switched on/off. Source background: (Vandysheva et al. 2012)

Additionally, some visualization prototypes enable user navigation, object search and attribute query (i.e., a step beyond selection); these prototypes include one from Korea (Jeong et al. 2011) and a visualization prototype built on CityEngine (Ribeiro et al. 2014). Going one step further, Navratil and Fogliaroni (2014) proposed a new model for 3D visibility analysis that integrates 3D Cadastre data in the context of urban planning.
To summarise this section, table 3 recapitulates the platforms, their functions and current gaps identified in literature.

Table 3. 3D cadastre platforms and their functions in the context of cadastre visualization

Platforms	Functions	Challenges
- Web/desktop - Open/proprietary - Fully functional (editing) or basic visualization only - Virtual and augmented reality - Gaming platforms	- Zoom in/out - Pan - Changing the colour, the type of symbol, the level of transparency, the shadow effect, etc - Spatial analysis - Navigation - Spatial Search - Attribute query - Stereo presentation	- Legal and institutional adoption - Interoperability of software - Absence of mobile devices - Interface for field surveys (not 3D) - Gap between 3D developers/users (e.g. gaming) and cadastral system developers/users

4. EMERGING TRENDS IN 3D VISUALIZATION

This section identifies a number of emerging research or trends in 3D visualization that may benefit 3D cadastral visualization. To facilitate the comparison, the topics are presented with the same groups as section 3.

4.1 Users and User Requirements

As noted in section 3.1, current research in 3D cadastre visualization does not include much user analysis and those assessments are not really initiated by standardized terminologies and approached. To this end, ISO, IEC and IEEE standardization on data quality assessment should be examined in more detail. For instance, the distinct notions of usefulness, usability and acceptability are required to conduct reliable investigations that integrate end-users. Usefulness/usability issues cover solutions which intended users can understand and find useful for decision-making. In this context, usability refers to the technical aspects of a visualization (Bleisch 2012; Landauer 1995), whereas usefulness addresses whether it does what the user needs. The usability of a solution may not guarantee its usefulness, and there are possibilities that a usable visualization tool would be totally useless in real life (Greenberg and Buxton, 2008). Usability studies (part of research into human-computer interaction)—such as heuristic evaluation, cognitive walk-through (Neilsen 1993) and studies using user testing and co-operative evaluation (Jacobsen 1999)—are also fundamental.

A starting point to understand the usefulness of 3D visualization may be appraised from the geovisualization cube of MacEachren & Kraak (2001). They propose three axes to assess geovisualization: 1) user or audience (public to expert), 2) interaction (low to high) and 3) information content (unknown to known). From the point of view of the cadastre, usefulness may be considered along the concept of multipurpose cadastre (Dale and McLaughlin 1999; Williamson et al. 2008) or along suitability for the purpose (Enemark et al. 2014). Integrating the third dimension in cadastre is a possible opportunity to involve new users or develop new markets as it forces current users and practitioners to re-examine their own mission or professional practice. Climate change, sustainable development, urban planning are important societal preoccupations, which now integrate 3D models of the Earth; land information is -should- be part of it. Capturing user requirements for on-demand mapping, dealing with different communities of users and establishing various user profiles would be benefit (Gould and Chaudhry 2012). Personalising visualization of the content of maps (2D/3D) according to the profile and location of final users would be useful in a cadastral context (Mac Aoidh et al. 2009). For a notary, an expert or a citizen, a same object (a building for example) could be represented differently following a simplified/complex geometry, other graphics (visual variables), and/or semantic information.

Acceptability comprises collective, political and legal factors of acceptance—does the solution conform to common practice, approved standards or laws. Applying user-centred design (which places the user at the focal point of any design process) in 3D Cadastre visualization research will help the designer to understand user requirements. Additionally, it prepares the user for the new visualization solutions from the very first stage of the work, and provides the benefit that working closely with the users will give developers of 3D cadastral systems an immediate understanding of the feasibility of their suggested approaches. For example, a desktop-based system may pose technical issues in an organization with limited IT expertise.

As mentioned, an additional important factor to consider is the learning curve for users moving into a 3D environment. Preliminary tests have been done (Lu et al. 2016) comparing interaction in 2D and 3D GIS using ESRI's ArcMap and ArcScene for seven users (Nielson 2000 notes that five users are sufficient for usability tests). Their results show that while all seven users were able to find a given location and measure a distance, they struggled with more complex tasks in 3D. In particular, only one of the users managed to fly through a route, and only five managed to measure the height of a building. Similar experiments are required for cadastre users.

Semantics-driven visualization is another possible direction to explore to guide users through 3D visualization parametrization since it would result in adding formalized knowledge of a certain domain, user's experience, interaction and learning aspects to support visual task (Nazemi et al. 2015). Semantics-driven visualization would allow adding formalized knowledge of a certain domain, user's experience, interaction and learning aspects to support visual task (Klima et al. 2004; Mitrovic et al. 2005; Posada-Velásque 2006). Attributes and information from data, users and resources can then enrich visualization applications to decide how to represent data effectively according to defined rules. Smart applications can think and choose appropriate methods of visualization for a specific user for specific tasks. For example, if the user profile specifies the type of user and tasks (semantic information), needs and resources (e.g. device, internet bandwidth, and processor speed) might be specified for the application. Ideally, the application can automatically provide a customised visualization for the specified user according to semantic information acquired from users (Shojaei, 2014). For example, Neuville et al. (2017) is proposing a decision support tool that facilitates the production of an efficient 3D visualization. They propose a set of predicates and truth conditions between two collections of entities: on one hand the static retinal variables (hue, size, shape…) and 3D environment parameters (directional lighting, shadow, haze…) and on the other hand their effect(s) in achieving a specific visual task. Their approach could be interestingly applied to cadastre context.

Ethical issues may also be discussed when 3D visualization systems are exploited since the visualization pattern may benefit to promote (or not) one aspect or hide another. Monmonier demonstrated long time ago (1996) how it is easy to lie with maps and in 3D visualization, this issue is even more prevailing. For instance, 3D model visualization can appear so similar to the reality, that user may be confused; this is especially true when photorealistic rendering is applied. The 3D Ethics Charter[5] is one of the initiative that we may highlight here (Pouliot et al. 2010) or the Statement of Values for the Geomatics professional community (Pouliot et al. 2013). Sheppard also conducted several studies on this topic, promoting a code of ethics for 3D landscape visualization (Sheppard 2000; Sheppard and Cizek 2009). This issue of 3D ethics in the context of 3D cadastre application has not been examined yet.

4.2 Information to Visualize and Semiotic/Rendering Aspects

As noted above, there is a need to model a wide range of complex real-world and virtual objects in any 3D Cadastral system. This contrasts sharply with the need to present a simple, understandable visualization to the end-users of any system. A number of research areas in GIS and beyond can assist with this challenge. Although this publication does not address the topic of data modelling, how data are organised and modelled may influence the visualization design.

[5] http://ge.ch/mensuration-officielle/media/mensuration-officielle/files/fichiers/documents/brochure_en_lr.pdf .

Some mapping and modelling practices like data generalization, multiple representations or occlusion management are techniques that may be investigated to improve data communication and thus visualization, and provide the additional benefit of a more nuanced understanding of user needs for 3D cadastral visualization, recognizing that a 'one size fits all' approach may not be appropriate. Correspondingly, metadata and data cataloguing also need to be refined in the context of 3D model (Zamyadi et al. 2014), the same apply to 3D cadastre.

4.2.1 Level of Detail

Research into 3D generalization has been carried out by several authors, including Fan et al. (2009), Glander and Döllner (2009), Mao et al. (2011) and Meng and Forberg (2007). As with 2D generalization, a key purpose here is to provide a visualization that suit visual tasks for a specific user, emphasizing key features and removing or aggregating others (Robinson et al. 1995). The question of level of detail (LoD) as proposed by CityGML (Kolbe 2009) and formalization of LoD (Biljecki et al. 2014) is an interesting concept to examine. In current cadastre system, legal objects are most of the time visualized individually and are displayed as small as necessary to represent RRRs (van Oosterom et al. 2011). Unlike physical objects, legal objects cannot be generalised in cadastres. For example, at a city level, it would be misleading to generalise and merge legal objects (e.g. lots in a high rise) and visualise them in a single volume. Therefore, the traditional concept of LoD is not applicable to legal concepts (Shojaei, 2014), unless it is used to go beyond 3D building visualization and integrates legal, non-visible objects or boundaries, or their corresponding RRR as a specific LoD. The work of Gruber et al. (2014), applying LoD for the German Cadastre, is a first step in this direction. A similar argument might apply to traditional approaches to generalisation - for example, can RRR be aggregated conceptually in a similar way to individual buildings being aggregated into a single block.

4.2.2 Enhancing techniques

3D generalization and LoD are generally static—i.e., the process is run once. However, having multiple representations of the same object can also be adapted to overcome occlusion issues in a 3D environment—i.e., objects that prevent a user from visualizing or selecting an object of interest. Enhancement techniques such as altering the viewing direction, and depth clues may increase the spatial awareness of the viewer (Zhang et al. 2016). Elmqvist and Tsigas (2008) presented an interesting and detailed review of 50 techniques in this area, including multiple viewports and virtual X-ray tools. For example they proposed an occlusion management called dynamic transparency that improves object discovery, and they applied it for 3D games, see figure 20.

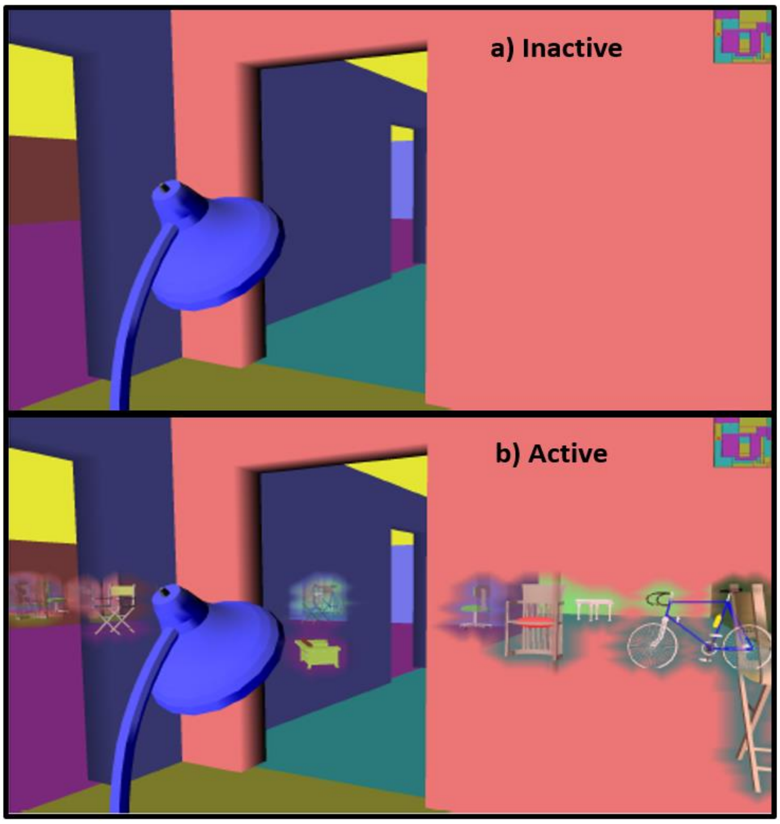


Figure 20. First-person view of the application of dynamic transparency (source Elmqvist 2006)

Cutaways and cross-sections (which are traditionally used in 2D cadastral mapping) also provide a direct technique to remove visual occlusion. Nevertheless, cross-section or cutaway illustrations are challenging to compute in keeping consistent material and surface textures in a vector boundary modelling. Li, Duan et al. (2015) explored semantic volume texture (SVT) model to overcome some of these computational challenges. They proposed an approach that rasterize the 3D model, while embedding pre-extracted semantic hierarchy and volume texture and rendering. Figure 21 illustrates one of their results. Voxel modelling and successive visualization have not yet been explored in cadastre application.

Fogliaroni and Clementini (2014) and Billen and Clementini (2006) applied the multiple viewport technique by splitting the 3D space in order to model the visibility between 3D objects. They proposed a new 3D visibility reference framework based on qualitative spatial representation, more reliable to human visual perception. Figure 22 shows an example of this framework. This technique may be suitability applied in the context of modelling and then revealing servitude of view while the concept of qualitative positioning (on left, above, etc.) better correspond to the user perception of how restrictions affect its own land usage.

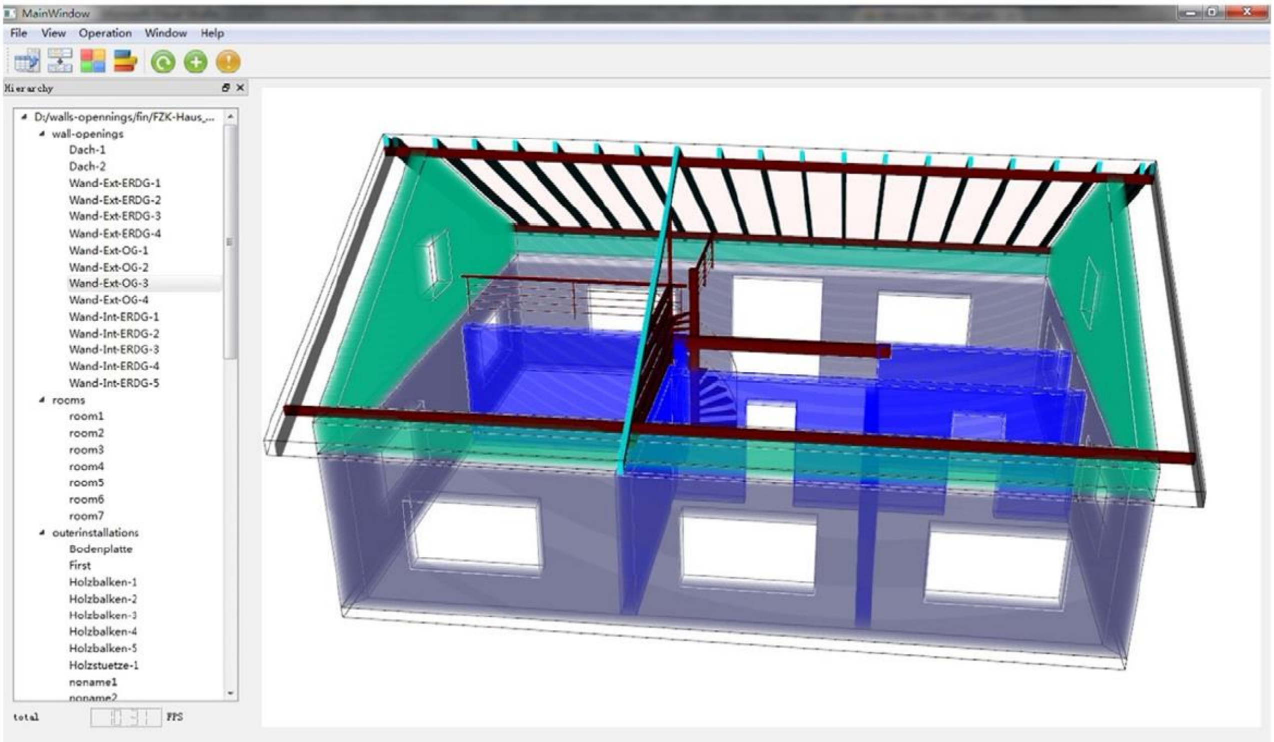


Figure 21. Example of semantic volume texture (source Li, Duan, et al. 2015)

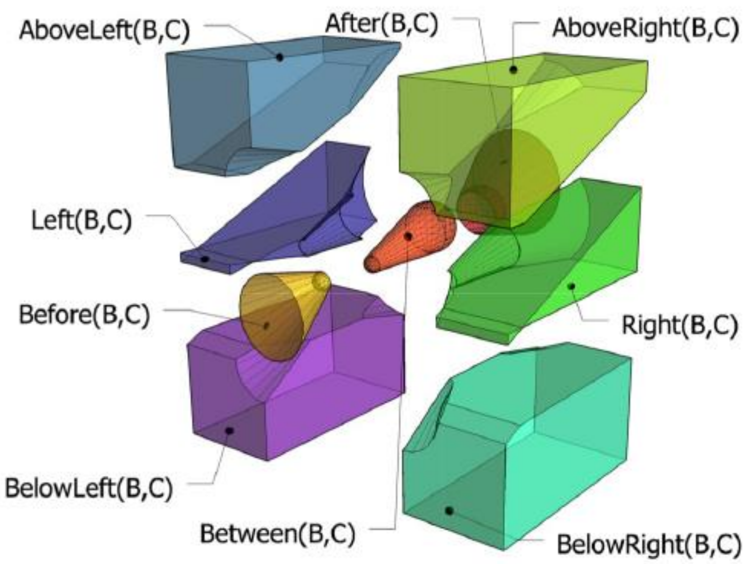
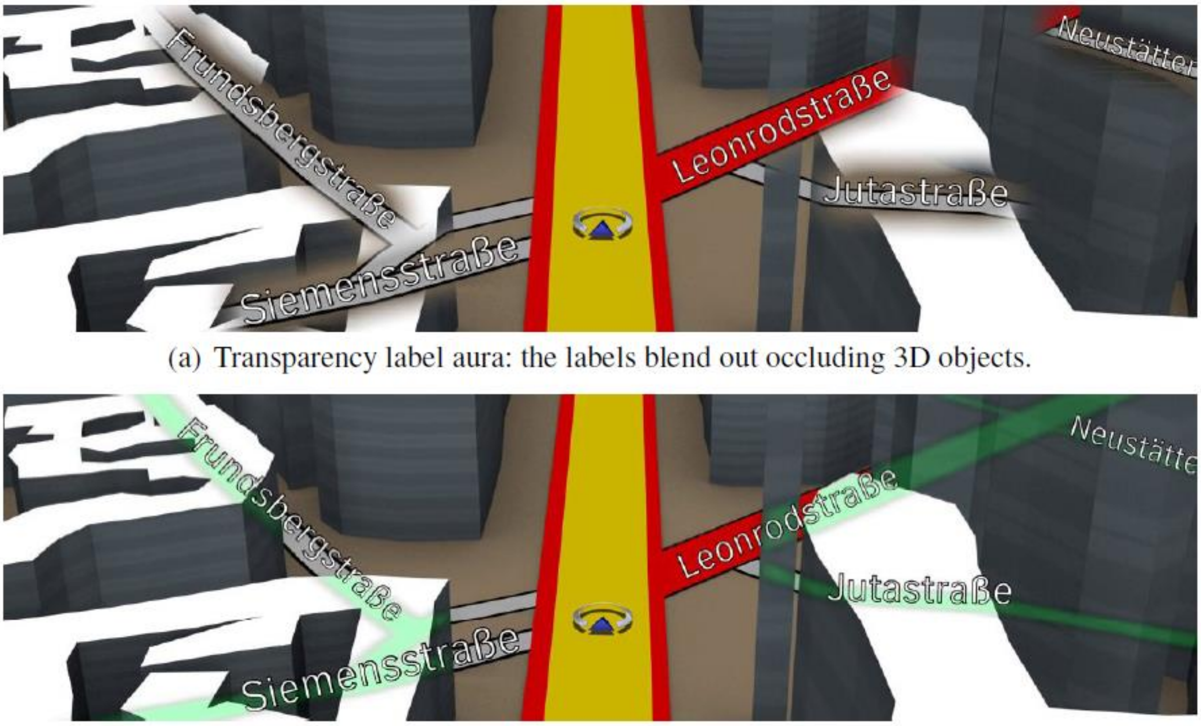


Figure 22. Visibility model in 3D space (source Fogliaroni and Clementini 2014)

4.2.3 Annotation and Labelling

3D annotation, as previous noted as of main importance for cadastre users, needs to be taken in consideration in the visualization process since it is a critical issue for spatial orientation in 3D model. For example, Vaaraniemi et al. (2012) propose to enhance the visibility of annotation (labels) in 3D navigation maps and they tested various techniques with users. Figure 23 shows two examples of approaches used to preserve the visibility of textual labels. Their approach looks much appropriate for cadastre application.



(a) Transparency label aura: the labels blend out occluding 3D objects.

(b) Glowing roads: the roads shine through occluding 3D objects.

Figure 23. Example of how to enhance the visibility of annotation (source Vaaraniemi et al. 2012)

Focusing on the mixed geometry/attribute environment that reflects a 3D cadastral situation, Jankowski and Decker (2012) presented a comparison of two modes of interacting with 3D data on the web, where hypertext and 3D graphics are mixed (see figure 24). They experimented with labelling and annotating 3D interactive illustrations in three settings: annotations attached to objects using translucent shapes, located within the objects' shadows, or with the areas showing the 3D model and text being separated. They conclude that the last method is best for long text, since users can explore the scene without text interrupting the view. The first setting is best for short texts, a result directly transferrable to 3D cadastral interfaces.

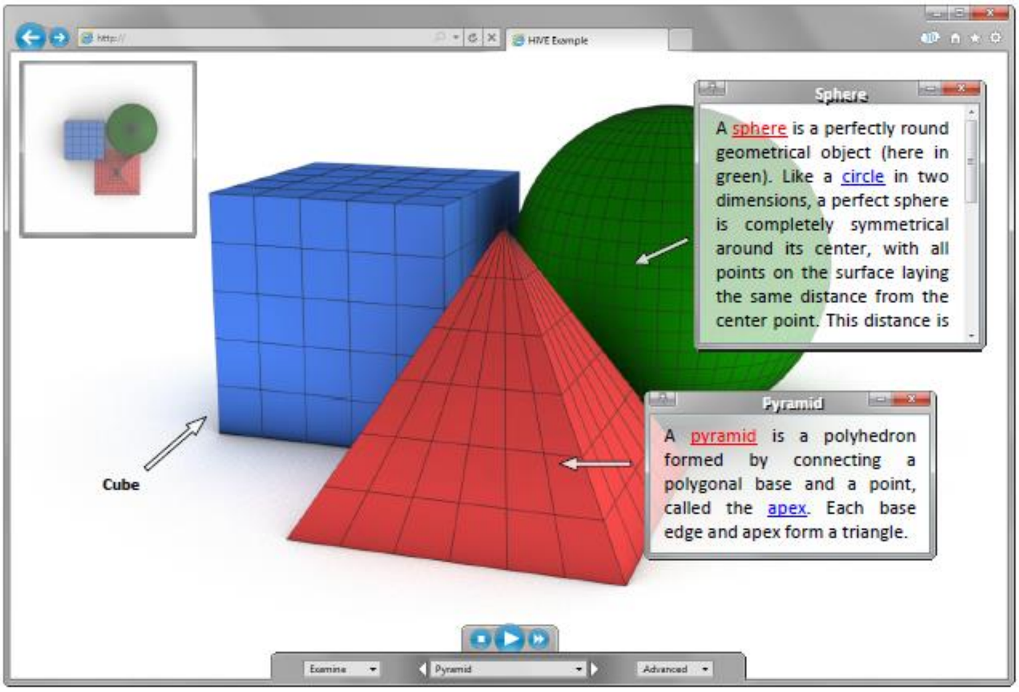


Figure 24. Illustration of the combination of hypertext and 3D graphics (source Jankowski and Decker 2012)

In addition to this, an investigation into other visual enhancement techniques in the 3D cadastral environment should be realized in order to take advantage of work done by Métral et al. (2012) and Shojaei et al. (2013) on using text for annotation, work done by Trapp et al. (2011) who added a new arrow symbol above an original symbol to attract the viewer's attention, and work done by Turkay et al. (2014) who present the concept of an attribute signature to help the visual analysis of geographic datasets.

4.3 Visualization Platforms

The use of 3D environments and interaction topics mentioned in *Section 2.2* above—web-based, mobile-based, virtual reality, augmented reality or full immersion—will in turn impact the ways in which the user can interact with the environment and objects within it, and 3D cadastral research should also be expanded to include research in the broader field of computer science and, in particular, 3D gaming.

4.3.1 3D Data Modes of Display

Approaches here range from those available on a standard desktop computer or mobile device such as a tablet (no immersion in the environment) through augmented reality (partial immersion) to those requiring very specialized hardware (full immersion), which can in turn be very expensive.

Web-Based 3D Visualization

In addition to the 3D-cadastral prototypes mentioned in Section 2, other researchers are experimenting with WebGL or OGC Portayal. An example of this can be found in Milner et al. (2014), who presented a 3D-enabled web GIS with full selection and editing functionality. Resch et al. (2014) used WebGL to build web-based 3D+time visualization application for marine geo-data and Chaturvedi et al. (2015) presented a web-based virtual globe able to integrate and display very large semantic 3D city models, developed with Cesium JS, an open-source JavaScript library for 3D globes and maps. For cultural heritage dissemination purpose, Koeva et al. (2017) proposed a web-based portal that use spherical panoramas, videos and sounds. Ferraz and Santos (2010) combined Spatial OLAP[6] tools with virtual globes to facilitate the discovery and exploration of multidimensional data (i.e., thematic, temporal and spatial data) on 3D maps. Devaux et al. (2012) conceived a web framework, named iTowns[7], to visualize 3D geospatial data, Lidar data and street view images. iTowns is based on WebGL and offers also tools for 3D precise measurements.

Augmented Reality
Rooted in the concepts of spatially enabled smart cities (Coleman et al. 2016), augmented reality (AR) is certainly one promising field to explore for cadastre application (Hugues et al. 2011). Figure 25 illustrates a number of possible applications of AR devices to land management purposes. Exploiting AR also results in new challenges to be considered (van Krevelen and Poelman (2010). For example, Duinat and Daniel (2013) and Schall et al. (2013) explored the applicability of AR devices for interactive visualization of underground infrastructure. Pierdicca et al. (2016) tested AR devices in the context of natural resource maintenance while Lee et al. (2012) used it for city visualization. Figure 26 shows the example of AR system applied to the 4D visualization of data uncertainties (olde Scholtenhuis et al. 2017). In this last example, the level of uncertainties, categorised into three classes (standard, estimated, surveyed location), is used to generate variable cylinder shapes. Integrating the visualization of uncertainties information also looks appealing in the context of cadastre application.

[6] OnLine Analytical Processing.
[7] http://www.itowns-project.org/

Check apartment subdivision

Source Dyer 2015

Confirm easement location

Source http://geospatial.blogs.com/geospatial/augmented-reality/

Locate underground networks

Source Rajabifard 2015 and Grant 2012

Inform about occupancy

Source https://petitinvention.wordpress.com/2009/09/04/red-dot-design-concept-award-2009/

Figure 25. Examples of possible application of augmented reality devices to land management purposes

Figure 26 Augmented reality and fuzzy concepts to enable the 3D-representation and visualization of uncertainties for underground utility data (Olde Scholtenhuis et al. 2017)

Immersive Virtual Environments

Geovisualization laboratories are emerging and they give access to a variety of tools and instruments dedicated to interactive viewing of geospatial data. Some interactive, physical and virtual environments (VE) could be useful in the context of 3D cadastre learning. Research has emerged in the past ten years: displaying 3D virtual environments on walls (CAVE2) and interacting by using the CAVE2 wand controller, the prototype CAVE Sphere device or tablet devices (Febretti et al. 2013), exploiting BIM data in virtual reality environment for construction and architecture in the Callisto-SARI project (Genty 2015), interacting with the Google Earth virtual globe by using the Microsoft Kinect (Boulos et al. 2011), enhancing interactive learnings with students about flood risks by using a 3D CAVE (Philips et al. 2015). Figure 27 presents the example of Casala Centre (Netwell/CASALA, Dundalk Institute of Technology[8]) to demonstrate the 3D CAVE. It shows a virtual apartment in a complete immersive environment modeled from data collected by 3000 sensors positioned in the real apartment (in using 3D glasses, people can freely interact with the 3D model). There is also a dearth of research regarding stereoscopic and immersive virtual reality for visualizing 3D parcels (Buchroithner and Knust 2013).

[8] https://www.dkit.ie/research/research-centres-groups/ict-health-ageing/netwellcasala

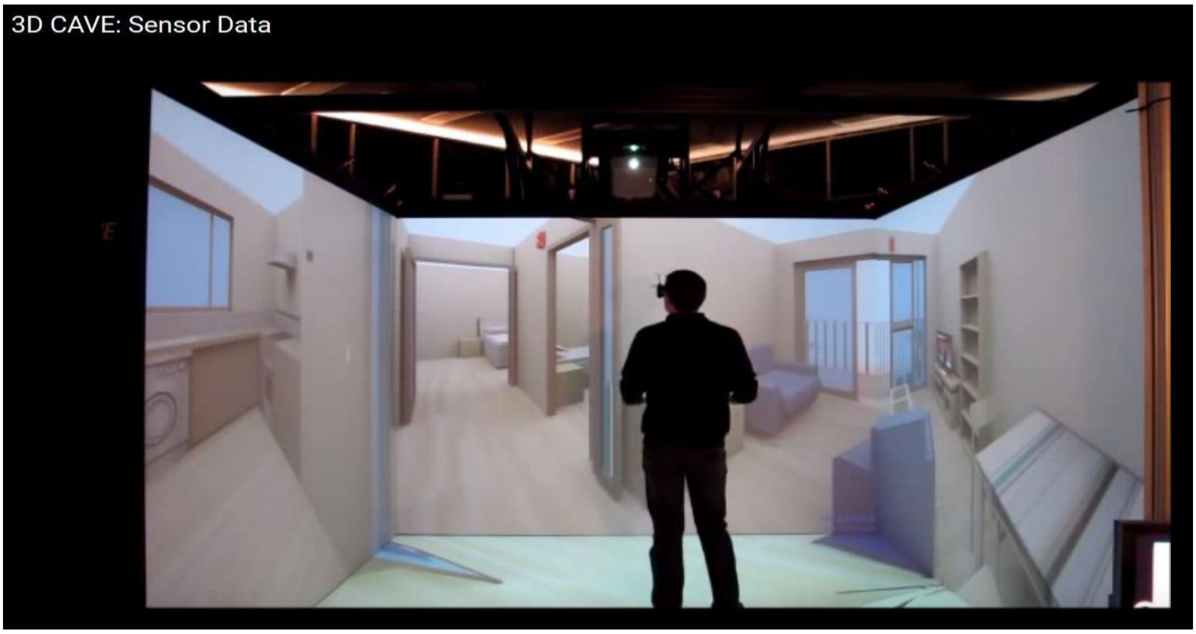


Figure 27. Example of 3D Cave for an apartment (source www.casala.ie)

Other immersive and interactive works concern holographic technologies including Zebra Imaging[9], Musion (http://musion.com), Leia 3D[10] and Holusion[11]. In a geovisualization context, a first holographic map was produced in 2011 by DARPA in the "Urban Photonic Sandtable Display" program in collaboration with Zebra Imaging[12] (see figure 28). Combining these novel holographic technologies with 3D cadastral objects could be considered as an attractive means for private or public institutions to promote cadastral systems, although the expense means they are beyond the reach of the everyday user. It could accelerate the decision making process in focusing on the message rather the medium.

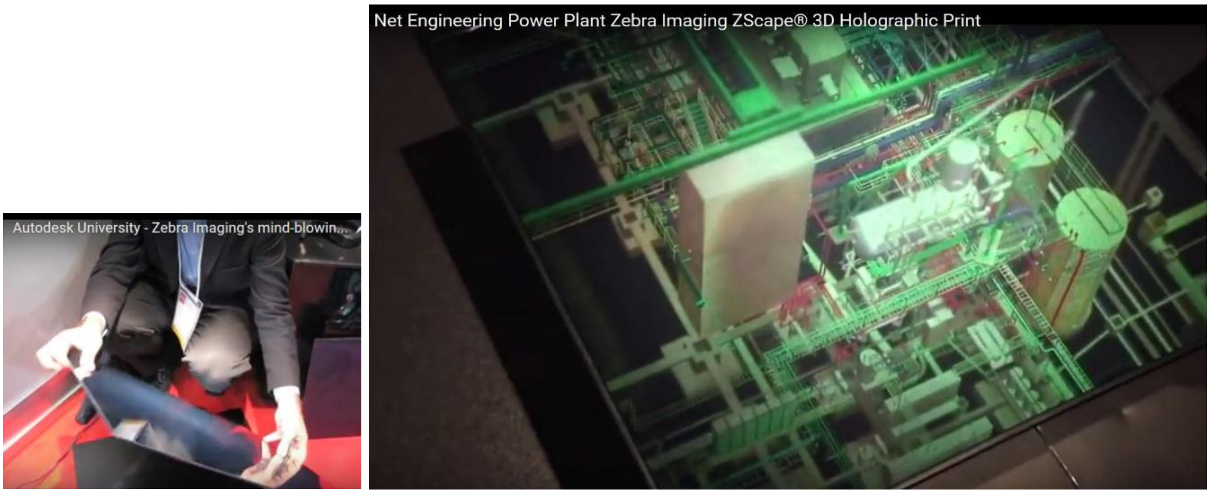


Figure 28 ZScape 3D holographic viewing (source www.zebraimaging.com)

[9] www.zebraimaging.com
[10] www.leia3d.com
[11] http://holusion.com/fr
[12] www.nextbigfuture.com/2011/03/darpa-has-3d-holographic-display.html

3D Gaming

Users of 3D cadastre systems are for the most of them beginners when working in 3D environments. For this reason research carried out in 3D Gaming may also be beneficial since it may provide additional learning from both technical and user points of view. In particular the concept of Serious Games appears relevant here – defined as games which encourage active and critical learning through a gaming environment, where users enjoy pursuing challenging tasks, and where competition may also be involved (Kosmadoudi et al. 2013). 3D examples include games used to teach users how to use complex CAD systems, how to navigate a fork-lift truck, and research into collaborative engineering design. Minecraft offers to user a new opportunity to build a virtual environment to help students to reproduce and understand some phenomena (Formosa 2014; Short 2012). In the same way, simulated LEGO blocks (as cube forms) could be assembled to build virtual scene from the real world. Yuan and Schneider (2010) built an indoor scene with LEGO cubes in a context of 3D route planning.

4.3.2 Interaction – Moving Around in the 3D World

Traditionally, interaction with 3D Cadastral Systems takes place via a screen and a mouse. This is in great part due to the wide availability and low cost of these tools (Ortega et al. 2016). These options, however, have the disadvantage of not providing easy access to a full 6 Degrees of Freedom—(3 * rotations and 3* translations), required for 3D interaction. A number of tools commonly associated with 3D gaming, as well as emerging interaction options, are perhaps worth considering. These include (from Ortega et al., 2016): keyboards and mice, controllers such as the Nintendo Wii, joysticks, inertial sensing devices (e.g., a combination of gyroscopes and accelerometers on a smartphone) and head-mounted displays – such as the Oculus Rift or Microsoft Hololens. For instance, SketchUp now offers a viewer for Microsoft Hololens that enables mixed-reality visualization as part of collaboration scenarios (“what if” design scenarios).

Related usability research may guide the choice of interaction mode for 3D cadastral systems. For example, Farhadi-Niaki et al. (2013) compare static and dynamic gesture interaction, as well as haptic options (a haptic mouse) as interfaces to 3D games, concluding that static gestures performed better in terms of time and precision and naturalness of the interaction while the 3D mouse was easier to use, but caused more fatigue. Additionally, there is extensive usability research examining specific tasks that users perform within the 3D environment, including object selection, retrieving information about objects, capturing new data and moving around the environment. In a study that is perhaps close to the needs of 3D cadastral users, Cashion et al. (2012) looked at object selection in the context of dynamic, dense environments, concluding that a ray-casting approach—such as that provided by the Wii remote—is best for static, low-density environments. For high-density scenes, however, an ‘expanded’ approach—where the user is offered a grid of possible targets once the ray has been cast—is more efficient (Teather and Stuerzlinger 2013).

Jankowski and Decker (2012) presented a comparison of two modes of interacting with 3D data on the web. They also described research into two interaction modes for “travel”—movement around a 3D VE—a simple mode, where the user can click on hyperlinks in the 3D view and go to fixed viewpoints; and an advanced mode, where the user is free to explore, concluding that the opportunity to swap between modes as the user requires provides the most efficient interface.

Interactive lens for visualization is a novel tool allowing to view other visual data through a spherical surface above a basic visualization like a map (Tominski et al. 2014). This interactive tool could be useful in a context of 3D cadastre in order to interact with 3D objects for viewing various representations and more details of these same objects. Magic lenses based on additional physical supports like a paper with a tabletop (Spindler and Dashselt 2009) or with tangibles devices in virtual 3D environment (Brown and Hua 2006) already exists.
Finally, adapting interfaces and interactions to the context of usage according to user profiles, their environment (physical or social) and platform (hardware or software), as proposed in the field called plasticity of user interfaces, may also be of interest for 3D cadastre applications, with the work on 3D plasticity by Lacoche et al. (2015). An extensive review was first published in *3D User Interfaces: Theory and Practice (*Bowman et al. 2004), and more recently in Ortega et al. (2016).

4.4 Beyond 3D Visualization

The vast majority of the papers discussed visualization from the point of view of "geo"visualization (geometric representation). To conclude this review, we though interesting to open a short parenthesis on time visualization and visual analytics that may help us to enlarge the typical notion of 3D digital representation of geospatial (cadastre) data.

4.4.1 Integrating Time

Adapting time-based 2D visualization and interaction could be of interest for suggesting new time-based 3D cadastral data. The space-time cube is a well-known application combining time series as the third dimension with 3D maps (Hägerstand 1970; Kwan and Lee 2004). This 3D environment is also mainly used to visualize and analyse temporal information in the space for movement data (Kraak 2003). Displaying a temporal division of parcels can be easily achieved (van Oosteroom and Stoter 2010) and time-based interactions in such a space-time cube have already been studied by Bach et al. (2014).
Ringmap is another method to explore to interact with data in order to visualize time series. For example, Zhao et al. (2008) present different representations of time series in a geovisualization point of view with a specific focus on ringmaps. Wu et al. (2015) also integrate ringmaps in their analysis of Dutch temperature data. In the context of real estate transaction monitoring or tracking, such representation would be helpful to discover spatio-temporal patterns. For interactions, temporal navigation methods by direct manipulation are designed for 2D and 3D environments (Kondo and Collins 2014; Wolter et al. 2009).

4.4.2 Integrating Visual Analytics and Big Data

Visual analytics offer techniques and tools that synthesize information and derive insight from massive and dynamic data by providing interactive visual interfaces (Keim et al. 2008). It proposes a combination of graphs, dashboards, statistical views, etc. For instance, managing and thus visualize a huge volume of data has recently emerged the research field or "Big Data". Of direct relevance to 3D cadastral systems is the work by Olshannikova et al. (2015), examining the potential of integrating Big Data in different augmented and virtual environments. Li, Lv et al. (2015) also present a new 3D globe, named WebVRGIS, able to display multiple types of big data from Shenzhen city. Preliminary researches are also started by Drossis et al. (2016) about the visualization of big data in an ambient intelligent environment.

All these researches on big data give us an opportunity to explore 3D cadastre from another point of view.
As part of big data and visual analytics, GeoBI (Geospatial Business Intelligence) systems offer motivating opportunities to take into account 3D cadastre model and data. In fact, GeoBI is "an intelligent coupling of GIS tools with Business Intelligence (BI) technologies to suitably exploit, analyse and visualize geo-spatial part of business data (e.g. borders, places, addresses, GPS coordinates, routes, etc.)" (Diallo et al. 2015). Spatial OLAP tools provide GeoBI client interfaces (Rivest et al. 2005). With such clients, combination of Spatial OLAP tools with virtual globes have already be made in order to facilitate the discovery and exploration of multidimensional data (i.e. thematic, temporal and spatial data) on 3D maps (Di Martino et al. 2009; Ferraz and Santos 2010).

5. DISCUSSION AND CONCLUSION

This paper provides a synthesis of current research and development activities in the context of 3D cadastral visualization. It shows that the topics vary from the identification and characterization of cadastral data, to symbolization and realization of visualization. In each case while 3D cadastral visualization can benefit from the work carried out in related fields – gaming, human computer interaction, augmented or virtual reality and so forth – it is important to realise that unlike other domains the data to be visualized in 3D must be linked not only to physical objects but especially to legal boundaries, which can range from the boundary of the parcels, easements, restrictions, and to the distinction between common and private properties. Additionally, we need to recognize that, while closely aligned, cadastral systems are distinct from engineering or urban data – in particular due to the legal aspects, and the challenges of visualizing information that does not have a 1:1 correspondence with physical features and thus could not be visually controlled in the real world (cadastre boundaries are what we called *fiat boundaries*). This adds an additional level of research to ensure that any solutions are fit for purpose, and highlights the need for interdisciplinary collaboration with those having cadastral expertise and experts from other domains. There is still a need to diversify the research domains considered in order to enlarge the audience and, consequently, disseminate the challenges and innovations of 3D cadastral visualization. Challenges to be addressed include the following:

5.1 Understanding User Needs and Functional Requirements

Understand user needs is perhaps the most fundamental of all the challenges, as it is only through this process, and via close collaboration with users, will it be possible to migrate from a 2D to a 3D visualization. To understand the specific needs of 3D Cadastre users, researchers need to meet and engage the professional end-users and be part of their day-to-day activities. Importantly, users do not only include notaries, land lawyers or land surveyors – in fact, the participation of a wider spectrum of cadastral users—e.g. urban planners or the general public—is necessary.
Functional requirements are one aspect of user needs to explore – i.e. what do users expect from the 3D visualization software in terms of performing visualization tasks (cross sections, viewpoints, visualising hidden objects, navigating in a 3D world, providing details about RRR) but also the identification of spatial relationships between features (spatial relationship of touch, cross, overlap). A key difference from other domains is the fact that users of 3D cadastre may not be using the software on its own, but instead would be using it in conjunction with, for

example, the production of a report. Additionally, and again in contrast with many other 3D projects, maps (and associated cartographic principles) have been around for a thousand of years, and 2D maps and vertical profiles are still perceived as valuable solutions, and must not be excluded from any research.

These requirements are central to allowing users to accomplish their daily tasks. However, integrated 3D visualization tools embedding these are currently missing, with some functionality (e.g. cross sections) being present in CAD/BIM and other elements (e.g. spatial relationships) in GIS. More specifically, to date, much of the 3D cadastral visualization approaches have focussed on ownership boundaries rather than the challenging visualization of right restrictions. While some tools offer editing capabilities (CAD/BIM and GIS tools such as ArcScene), some are restricted to viewing data. As the latter approach reduces the complexity of the software, both approaches may be relevant to different user groups. It remains to be seen whether we will be able to adapt existing tools to user needs or whether there is a role for a custom-built 3D cadastral toolkit.

5.2 Usability of Tools and Training

Moving from a 2D workflow to a 3D workflow involves a major cognitive leap and a steep learning curve, and users have to learn how to manipulate a 3D model, how to interact with the 3D model and to develop an understanding of the new semiotic approaches required for 3D. There is thus a major role to be played through both usability and semiotic research in this domain.

Building on the functionality highlighted above, linking the visualization system with a legal document such as a deed or title, which is well known to cadastre experts, would help by lessening the cognitive leap required to understand the purpose of the 3D system. We also need to participate in educational programs to help practitioners adapt to new realities and technologies, and in particular to ensure that undergraduate students are involved in 3D systems as part of their professional development. This new generation of citizens and professionals is much more aware of technologies and the acceptability level of new solutions is probably higher.

As researchers, it is also important to consider alternative approaches - in particular, given the extensive training and cognitive load required to move into 3D, a key question still needs to be highlighted regarding whether a 3D visualization systems is required to implement 3D cadastre (full or hybrid). Is it possible to work with 3D cadastre without having recourse to a 3D digital visualization system (Pouliot et al. 2011; Stoter 2004). This is particularly important to recall since 2D maps and vertical profiles are in many cases adequate to represent the geographic phenomena and support decision-making associated with land and property, and additionally professionals working in this area are accustomed to working with these 2D maps and profiles.

5.3 Organizational, Legal and Ethical Issues

Being involved in committees to adapt laws and regulations is probably a must. We, as specialists in spatial data processing and visualization, should be part of this step, placing the visualization in the context of land information system and requirement at the centre of discussions on the future of the profession and providing insight into legal options regarding registration, modelling and visualization using 3D approaches. As part of this, we should also better establish what to call the “3D product”, since in many ways the term 3D Cadastre is too

broad, whereas a term such as a "3D City Model" or "3D Map of a Road" is something tangible that is easily understood.
Ethical issues are particularly important, and are especially relevant in the context of property information – both from the standpoint of the information held as well as from the importance of understanding how users perceive and understand 3D visualizations. Promoting quality assessment, improving confidence in the 3D product and making limitations known are part of an overall ethical approach to 3D visualization. We need to understand how to do this while at the same time not over-complicating the visual interface and software system. Additionally, metadata analysis, and quality assessment for 3D cadastral visualization is an area where no research has yet been conducted.

5.4 Conclusion

As can be seen from this paper, the third dimension in cadastre may be perceived as an opportunity to enlarge the role of cadastre data and to involve new users or develop new markets. A number of positive steps have been made in this direction - in particular with regard to software to visualize such data - but much remains to be done. To conclude, we ask ourselves whether 3D models implemented, visualized, and integrated in the everyday duties of land administration players? Our analysis indicates that this is not yet the case, even though greater efforts have been made to increase users' participation. Changing habits is a long process and must be addressed step by step by confronting the challenges listed above. This is particularly the case in a domain such as cadastre application, which involves a legal framework applied to properties/possession/rights, and thus human values. Despite these issues, reality is three-dimensional, as is any decision-making associated with it, so it is important that visualization migrates to 3D.

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Explanation of the front and the back cover illustrations can be found on the back of the front cover.

This publication is the result from the International Federation of Surveyors (FIG) joint commission 3 ‘Spatial Information Management’ and commission 7 ‘Cadastre and Land Management’ Working Group on 3D Cadastres. The increasing complexity of infrastructures and densely built-up areas requires a proper registration of the legal status (private and public), which only can be provided to a limited extent by the existing 2D cadastral registrations. Within the FIG Working Group the concept of 3D Cadastres with 3D parcels is intended in the broadest possible sense: 3D parcels include land and water spaces, both above and below surface. The level of sophistication of a 3D Cadastre in a specific country will in the end be based on the user needs, land market requirements, legal framework, and technical possibilities. This FIG publication collects the best known practices related to 3D Cadastres in a single book organized in five coherent chapters:

Chapter 1. Legal foundations
Chapter 2. Initial Registration of 3D Parcels
Chapter 3. 3D Cadastral Information Modelling
Chapter 4. 3D Spatial DBMS for 3D Cadastres
Chapter 5. Visualization and New Opportunities

The FIG publication ‘3D Cadastres Best Practices’ provides a clear and comprehensive overview to both the newcomers and experts in the 3D Cadastres community.

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