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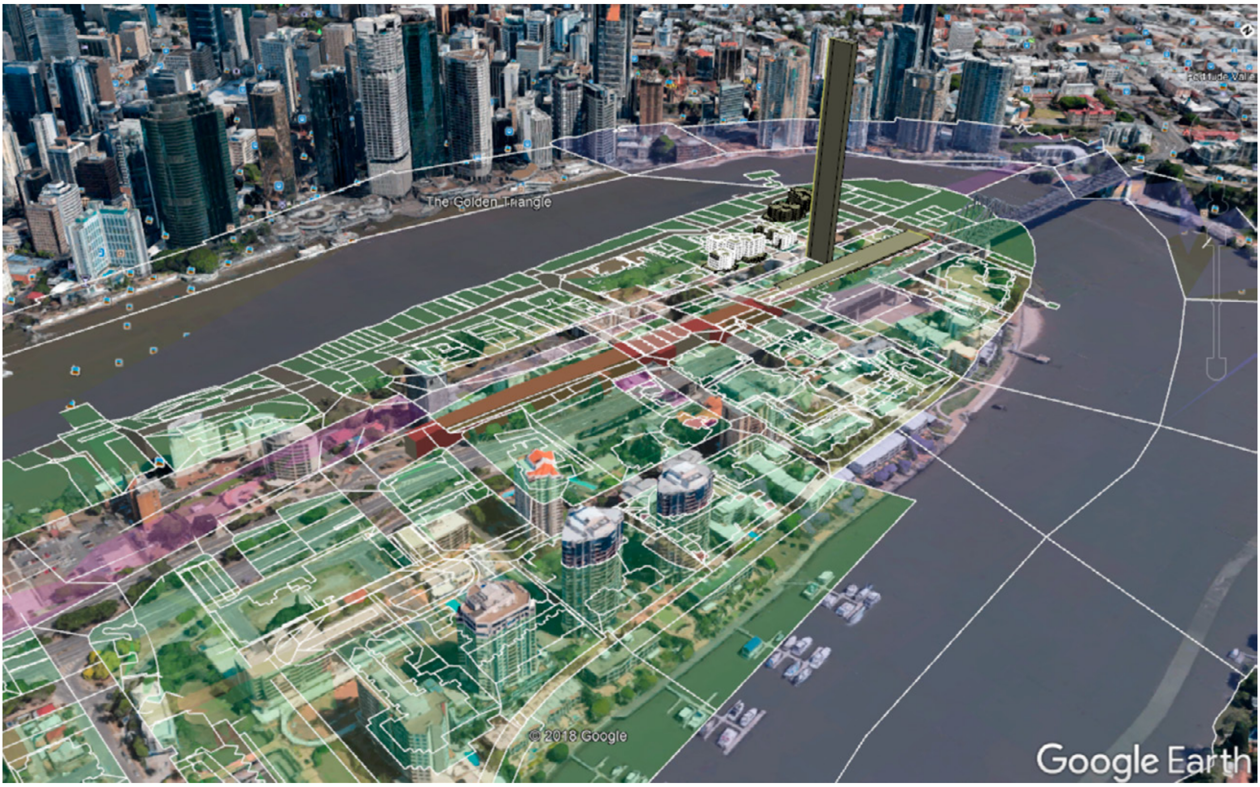
FIG REPORT

Best Practices 3D Cadastres



3D Cadastre Joint Working Group Commission 3 and Commission 7

INTERNATIONAL FEDERATION
OF SURVEYORS (FIG)

Best Practices 3D Cadastres

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Editor: Peter van Oosterom

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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 Barbara Cemellini, Marian de Vries, and Peter van Oosterom, TU Delft).

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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 4^{th} 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

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 the long version (available at http://www.gdmc.nl/3DCadastres/FIG_3DCad.pdf) this shorter version of about 80 pages is produced. The short version is 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.

The FIG publication '3D Cadastres Best Practices' has quite a long history. Many 3D Cadastral activities have been conducted during the past two decades: six 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). 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.

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).

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, 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

1.1 Introduction

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 while literature provides various examples of extensive research towards 3D Cadastres as well as 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 chapter compares and discusses 3D property concepts in fifteen selected countries, based on the authors' national experience, covering Europe, North and Latin America, Middle East and Australia. Each of these countries' legal system is 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. Selected countries are on different stages of introducing and implementing a 3D cadastral system; this may contribute to the detection of the main 3D real property concepts that apply as well as deficiencies and malfunctions that prohibit introduction of 3D cadastral systems, highlighting challenges that may have not yet surfaced. This chapter 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 Cadastre implementation, starting from countries with operational 3D cadastral systems, to others where there is yet no interest in introducing a 3D cadastral system.

3D cadastral objects in each country are presented, as well as differences in the regulatory framework regarding definition, description and registration. The chapter 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 abovementioned 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. Cadastres are being recognized as the core of land administration systems. The cadastral map 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 2D projectional presentation of RRRs on land parcels cannot accommodate complex, overlapping real property so it needs to be extended to three-dimensional (3D) space and properties. Controversy 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 space can no longer be unambiguously mapped onto the Earth's surface in 2D. Pressure on the 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, inter alia Sweden, Norway, Australian states of Victoria and Queensland, 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 selected 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 remaining of this chapter is structured as follows. Section 1.2 presents the topics examined in each of the fifteen case study countries. In Section 1.3, previously examined topics are summarised, while also their similarities and differences are presented and analysed. Section 1.4 presents the conclusions derived through preceding comparative analysis. The chapter ends by presenting issues emerging from current study that require further research.

1.2 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 (States 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 reason 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, as well as to prevent different apprehension of national legal concepts, aspects examined were required to respond to the following fields:

- 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 its 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.

Detailed presentation of each of aforementioned fields regarding each examined country can be found in this article's full online version.

1.3 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 1.1 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).

Despite their Civil Law origins, except for Common Law based states of Queensland and Victoria in Australia, each country is based on a different background reflecting both conceptional 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 Swed-

ish, 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 property 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 1. *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
Argentina	– Horizontal property – Easement – Subsoil occupation – Air space occupation – Surface right – Rivers and Lakes – Mines	– Horizontal property	– 2D (orthogonal projection)
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
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
Austria	– Tunnels – Condominiums – Wine cellars	– Tunnels[1] – Condominiums – Wine cellars	– 2D

Bulgaria	– Apartments offices – commercial buildings.	– Commercial buildings	– 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 with text that refer to complementary plans-PC that show vertical profiles and subdivision plans each floor. Altitude, height and volume are indicated on the PC-plans.
China	– Apartment -– Commercial buildings -– Underground facilities	– Apartment – Commercial buildings	– 2D
Costa Rica	– Horizontal property – Easement – Subsoil occupation – Air space occupation	– Horizontal property	– 2D (orthogonal projection)
Croatia	– Apartments – Office spaces – buildings and other structures – utility lines with associated facilities – traffic infrastructure – water and related objects	– Apartments – Office spaces	– 2.5D
Czech Republic	– Residential and non-residential premises, – Buildings, – Underground constructions (e.g. tunnels, metro, wine cellars), – Real properties given by the other law (e.g. dams, weirs, hydroelectric power station), – Culverts and bridges	– Residential and non-residential premises, – Buildings	– 2D
Greece	– Horizontal ownership/ condominium – Vertical ownership – Mines – SRPO – Infrastructures/ utilities	– Horizontal ownership/ condominium – Vertical ownership – Mines – SRPO – Utility servitudes	– 2D[2]
Jordan	– Apartment ownership	– Apartments	– 2D
The Netherlands	– Apartments – offices – commercial buildings, – infrastructure objects – tunnels – bridges	– Complex building in Delft	– 2D (some 3D)
Poland	– Tunnels (railway, subway etc) – apartments	– Land parcels – Buildings – apartments	– 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]

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: 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 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. Introducing 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.

1.4 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.

1.5 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. The importance of legal aspects of 3D cadastre is evident and research towards this direction should be continued and promoted, also motivating legal professionals to participate under 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 legal rules 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 the participating authors' national experience, 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.

CHAPTER 2: INITIAL REGISTRATION OF 3D PARCELS

Efi Dimopoulou, Sudarshan Karki, Miodrag Roić, José-Paulo Duarte de Almeida, Charisse Griffith-Charles, Rod Thompson, Shen Ying, Jesper Paasch, and Peter van Oosterom

2.1 Introduction

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).

A pertinent example of the above is what concerns property cadastre. Regardless of country, an up-to-date property cadastral system is fundamental for a 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 ownerships 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. As a matter of fact, 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 really 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. In other words, 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).

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 for 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 aims to be achieved in implementing a 3D cadastral model comprise the adoption to (Khoo, 2012):

- an official and authoritative source of 3D cadastral survey information,
- open source format for data exchange and dissemination, and to
- 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, onus 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 be also 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, 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 is 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 and for the jurisdictions, 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 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, surveyors, data managers and the registrars, however for the purpose of this chapter; 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, albeit 3D cadastre has been attracting researchers throughout the world for nearly a decade now to better register and spatially represent real world overlapping situations, 3D cadastral technology is only now emerging. 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).

2.2 Current Status of 3D Registration

The chapter provides a short report of initial registration of 3D parcels in various countries, highlighting the current status of cadastral registration as well as the procedures and workflows towards the establishment of a 3D cadastre. This inventory includes European cases (Croatia, Greece, Portugal, Sweden and The Netherlands), China and the Trinidad and Tobago Caribbean islands. More details concerning each examined country can be found in this chapter's full online version.

A comparison between the various countries featured common characteristics and differences that relate to cadastral registration issues (Table 2). The definition and use of the concepts of "3D parcels", "3D spatial units", "3D space or 3D objects", are among the essential issues that need to be clarified, in order to efficiently compare the different cadastral registration approaches and draw conclusions on best initial registration practices. It seems 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 where created/ updated in the 70ties or 80ties, 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.

2.2.1 Analysis of Categorisations of 3D Spatial Units

Moreover, the chapter provides details on the *classes of 3D spatial units* (Thompson et al., 2015), including *2D Spatial Units, Building Format Unit*s and *3D Spatial Unit*s within the set of which there are several categories, such as *Above/Below Depth or Height, Polygonal, Single-Valued, or Multi-Valued Stepped Slices, General 3D Spatial Units* and *Balance Spatial Units. Constraints* (validation requirements) on a cadastral database that can be at various levels of maturity have been also examined, including *Non-overlap-*

Table 2. *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

ping 2D spatial units, *Complete non-overlapping 2D, Non-base 2D spatial units, 3D spatial units represented as footprints, Simple 3D as extruded polygons*, *Non-overlapping 3D coverage*, *Complete non-overlapping in 3D* and *Non-base (secondary interest) 3D*.

2.3 Legal and Technical Issues

2.3.1 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.

2.3.2 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 1). 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. Common law jurisdictions and Civil Law jurisdictions may vary to some extent (Kitsakis and Dimopoulou, 2014; Ho et al., 2013).

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 1).

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 goes a very shallow. If an archaeological site lies beneath the land, the owner will have the opportunity to become familiar with numerous of 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 for this special permission has not been obtained.

Similar situation, in the opposite direction, is when building on the 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, to the owner of the parcel was left only a thin layer of the earth's surface and what is built. 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 is often necessary to obtain a concession. Rights are always established in "3D", 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 regarding are required.

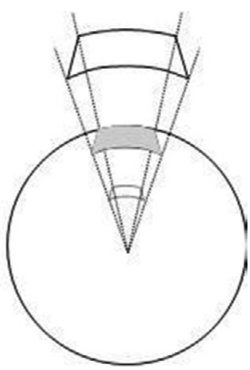

Figure 1. *Legal object.*

Registration of Legal Objects

Legal objects, as defined by the legislation, are materialized by physical objects. 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, the most commonly as a polygon which consists of boundaries. Polygon is 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. Predrilled parcel space cannot be easily modeled and visualized on 2D cadastral map.

Physical object that has 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 separated 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.

2.3.3 Technical Issues

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 the later 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 confliction test in 3D scene. The input or submitted data may have spatial relationships and conflictions with other existed data in database, either 2D data or 3D data surrounding them. If there are spatial occupation conflictions, the input data should be sent back to check their geometrics and locations. If there are small gaps between them, this situation is acceptable to ensure these is no spatial conflictions among the close 3D models, which is 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 existed models, including 2D overlay and connection, 3D topological connections, should be correctly recognized after the submission.

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 is 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 the 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.

2.4 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 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 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 (Section 2.1) 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 adopt 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, appropri-

ate 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, concerning the interaction 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.

CHAPTER 3: 3D CADASTRAL INFORMATION MODELLING

Peter van Oosterom, Christiaan Lemmen, Rod Thompson, Karel Janečka, Sisi Zlatanova, and Mohsen Kalantari

3.1 Introduction

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, 2014). 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).

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, 2013). 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.

3.2 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.

3.2.1 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.

3.2.2 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

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.

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 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).

3.2.3 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.

3.2.4 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 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.

3.2.5 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, and 4. Constraints Implementation. 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.

3.2.6 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 standardized information model also imports the expert knowledge. Standards enable interoperability. The most relevant standards organizations include ISO/TC211, OGC, EU INSPIRE. The overall objectives of ISO/TC 211 – Geographic information/Geomatics 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.

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. OGC and ISO TC211 have a close collaboration. The European Union promotes the Infrastructure for Spatial Information in the European Community Directive (2007/2/EC) for a wide range of applications (INSPIRE). A major task of the INSPIRE programme is to enable interoperability and, when feasible, harmonisation of spatial data sets and services within Europe. 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.

3.3 Standardized Information Models

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 (see Figure 2). 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).

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.

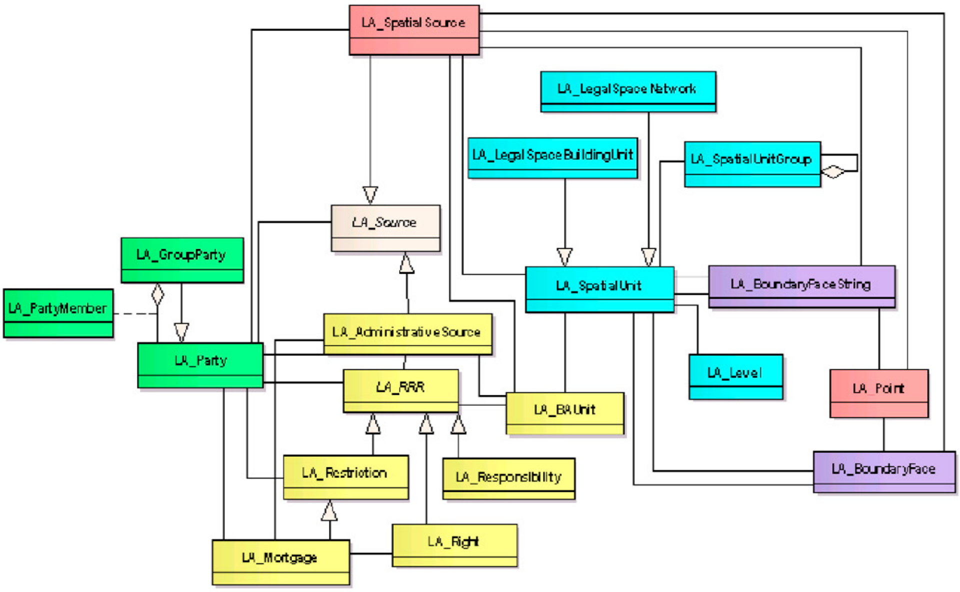

Figure 2. *Overview of the LADM classes: Parties in green, RRRs in yellow, Spatial Units in blue, Surveying in pink, and Mapping in violet (ISO, 2012).*

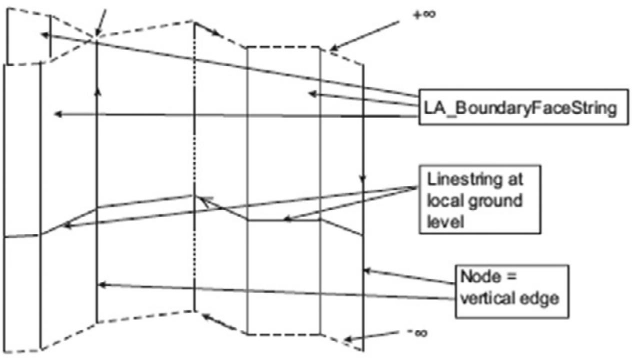

Figure 3. *LA_ BoundaryFaceString concepts (ISO, 2012).*

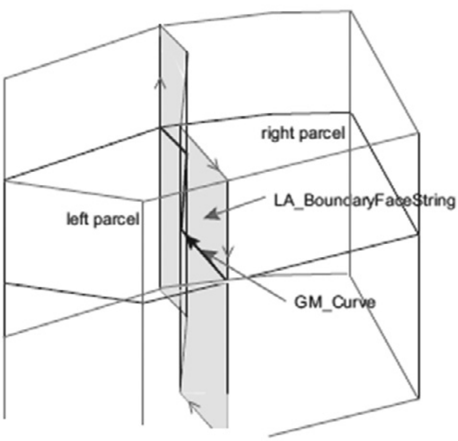

Figure 4. *LA_Spatial-Unit (parcel) defined by LA_BoundaryFace-String (ISO, 2012).*

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)[2]. This international standard defines the conceptual framework and 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).

3.4 Conclusion

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., 2015), Israel (Felus et al., 2014), Greece (Kalogianni et al, 2016), Trinidad and Tobago (Griffith-Charles and Edwards, 2014) and Turkey (Alkan and Polat, 2016).

What are acceptable (valid) 3D cadastral object representations, and how to create their 3D geometries (even non-2-manifold geometries) are still challenges and country decision dependent. 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.

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[3].

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

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2 http://www.iso.org/iso/catalogue_detail.htm?csnumber=32584 (accessed on 19 August 2016).
3 http://www.bsigroup.com/Documents/BSI_City Data Report_Singles FINAL.pdf (accessed on 23 August 2016).

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.

CHAPTER 4: 3D SPATIAL DBMS FOR 3D CADASTRES

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4.1 Introduction

With the advancements in computing and spatial science based technologies, the generation and usage of 3D data is now much easier 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 are still under development. There is no well-defined mass market with consumer-focused systems yet.
3. 3D data are largely managed in enterprise workflows with improved performance and scalability of existing workflows and as such allowing for bridging the gap between point cloud surveys, GIS, CAD, BIM. Traditional file handling moves to database management.
4. There is an increased demand for 3D data and clear understanding that 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 no 'best' solution is available, as the existing datasets are usually quite specific,
- Often a migration from simple data structures to complex data structures is inevitable,
- A higher number of economic and sustainability issues have to be taken into consideration in 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 based on 2D maps and databases supporting location-related policies (like

INSPIRE, building registers, land use plans, cadastral maps) have mainly 2D geoinformation (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).

4.2 Aspects of 3D Spatial DBMS for 3D Cadastres

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 including SDBMS should therefore enable:

- data models that handle a large variety of 3D objects,
- automated data quality checks,
- search and analysis,
- rapid data dissemination,
- 3D rendering and visualisation for different types of users.

This chapter asserts that while there has been significant progress 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 spatial database management system. 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 SDBMS 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 SDBMS including the hardware capabilities are elaborated in detail in the full version of the chapter.

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.

The detailed chapter available at http://www.gdmc.nl/3DCadastres/FIG_3DCad.pdf addresses in detail the following topics:

- The different types of 3D spatial representations (vector, voxel and point cloud),
- 3D spatial indexing and clustering,
- 3D geometries and 3D operations,
- 3D topology structures,
- The road from theory to practice,
- State-of-the art in spatial databases, and
- Spatial analysis: what is available and what is needed?

4.3 Challenges and Research Opportunities in 3D Spatial Database Management Systems for 3D Cadastre

Modelling and Storage of 3D Parcels

Beside the non 2-manifold geometries 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 5 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).

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).

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

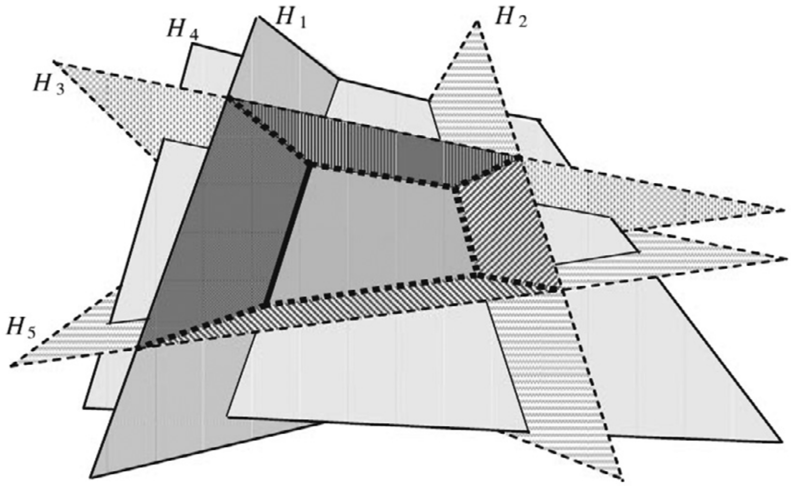

Figure 5. *A convex region defined by a set of half spaces (Thompson and Oosterom, 2006).*

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.

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.
- Extensive tests are needed to evaluate the performance of triggers in relation to 3D geometric operators and constraints.

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?"

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.

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., 2015). Motivated by the increasing gap between the computing power of GPU-equipped clusters and network bandwidth and disk I/O throughput, Zhang et al. (2015) proposed a low-cost prototype research cluster made of NVidia TK1 SoC[1] 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 thousands of

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

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 (Zhang et al., 2015).

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).

4.4 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 (Gorte and Zlatanova, 2016). 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 chapter 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.

Developments observed in the SDBMS domain indicate that more spatial data types, functions and indexing mechanisms are 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 shows advances in nD-array DBMS, reduction of file-based solutions, and increased efforts in development of modern Graphics Processing Units (GPUs) and massive parallel architectures for processing large-scale geospatial data. Our investigations have concluded on a promising solution for 3D cadastre and 3D registration, that is the 3D topological model TEN, synchronised with LADM specification. This topological model should be able to 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.

CHAPTER 5: VISUALIZATION AND NEW OPPORTUNITIES

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5.1 Introduction

Cadastral data is the core of land administration system and visualization. It is a fundamental component of many cadastral systems, providing instant clarity about the boundary of the land or any kind of property unit, such as a co-ownership rights, mining rights or marine rights that cannot be achieved via a textual description (Lemmens 2010; Williamson et al. 2010).

Traditionally, cadastral visualization refers to the visualization of ownership boundaries (e.g. legal boundaries) on maps and having access to descriptive data such as official measurements (length, azimuth, area, and owner's name) or legal documents such as title, deed or mortgage. Maps are by definition in 2D – they represent only two dimensions of the area of land (Oxford Advanced Learner's Dictionary). The map can include a planimetric representation (the length and the width of the area of land), or altimetry (the height of a specific portion of land or objects). Figure 6a shows a traditional cadas-

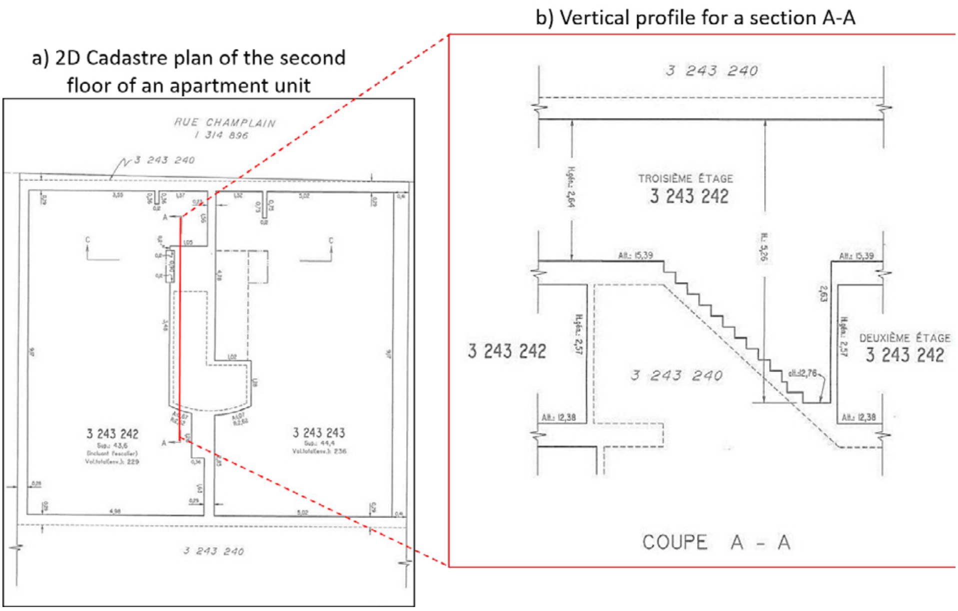

Figure 6. ***(a)*** *Example of cadastral plan and* ***(b)*** *vertical profile (section A-A) used in the Quebec cadastre system (extracted from Infolot-MERN1)*[1].

1 Infolot is the online system for Land register and Cadastre plan managed by MERN (Quebec Minister of Energy and Natural resources).

tral plan (2D) of land parcels for the jurisdiction of the province of Quebec, Canada, while Figure 6b illustrates a vertical profile (2D) that represents the vertical dimension of the condominium unit. While interaction with a 2D map may be possible (via geo-technology), the vertical and other profiles are mainly fixed, pre-defined when the cadastral system is created, and can only partially represent the complex 3D ownership and rights situations that are arising from today increasing urbanization. Adding an interactive 3D visualization system[1], 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, could overcome the 'fixed vertical profiles' issue.

Given the additional complexity introduced by visualization in the third dimension, this chapter first presents some fundamental concepts relating to the topic. We then outline the benefits of visualization in 3D, and present a summary of the related research challenges that must be addressed before these benefits can be fully realized by the cadastral community.

5.2 Understanding 3D Visualization

Moving from 2D map to a 3D interactive model involves a major cognitive leap and a steep learning curve – users have to learn how to manipulate a 3D model, how to interact with the 3D model and also develop an understanding of the new semiotic approaches required for 3D.

5.2.1 Concepts

Visualizing the third dimension of spatial data requires the Z dimension[2] in the visual field to be modelled to provide a perception of depth (Dykes et al. 2005; Kraak 1988). This depth perception can be achieved by using physiological cues such as eye convergence, binocular disparity or motion parallax and psychological cues like retinal image size, perspective or shadows, with modern technology taking advantage of both (Okoshi 1976). Furthermore, the ability to select, and therefore interact with, objects is fundamental to the success of any 3D system (Bowman et al. 2012). Human related phenomena including perception (psychological and physiological facets), memory, and cognitive science also may impact the design and the usage of visualization system (Miller 1956; Popelka and Dolez 2015; Ware and Plumlee 2005).

Consequently, addressing 3D visualization requires knowledge and expertise of various disciplines including cartography, computer sciences, image processing and photogrammetry. Related research areas also include information visualization (Ware 2012), cognitive science (Ware and Plumlee 2005; ICSC 2015), human-computer interaction (Popelka and Dolez 2015) and even 3D gaming.

5.2.2 3D Data Sources and Technologies

In order to be used for 3D visualization, data must be captured, stored and manipulated into a format appropriate for downstream use. 3D cadastral data 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). Figure 7 illustrates a number of approaches used for representing the

1 This chapter only addresses 3D digital system, not 3D printing that could be foreseen as a distinctive form of 3D visualization.

2 Note that in this case the Z dimension is distance away from the eyes.

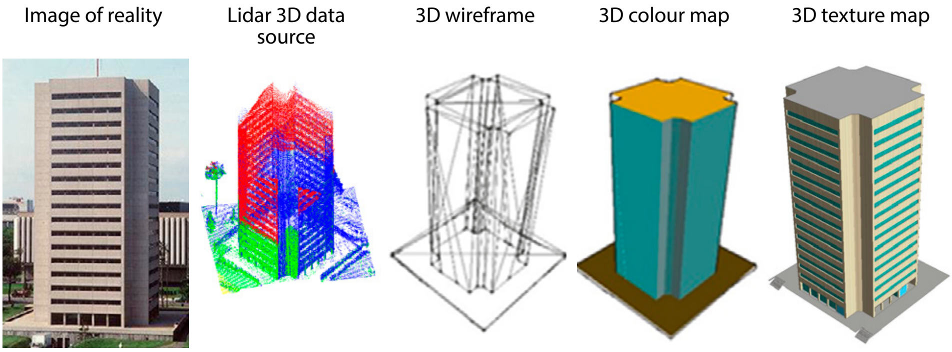

Figure 7. *Examples of 3D representation (the model represents one campus building at Université Laval, Ca).*

same building in 3D – ranging from a raw point cloud (Lidar) through a wireframe, colour and texture map.

More generally, many formats and standards exist in the domain of 3D. CityGML is as an open standardized Geography Markup Language (GML) data model for 3D city models (Gröger and Plümer 2012; Kolbe 2009; OGC 2012). The Industry Foundation Classes (IFC) is a standard widely in used in the context of Building-information modelling (BIM) and adopted by ISO-16739. A 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 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 (Parisi 2012) while OGC is working on 3D Portrayal Services (OGC 3D Portrayal 2012).

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 aided design (CAD) (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*).

Two groups of 3D visualization devices can commonly be identified – monoscopic display screens and stereoscopic 3D devices that mimic the human vision thanks to 3D glasses or stereoscopes (sometime called True 3D visualization). 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).

5.3 Benefits of 3D Cadastre Visualization

3D visualization is fundamental to achieving the wider benefits of 3D cadastral systems, as it enables users to explore representations of modern, complex, urban situations by providing interactive functionalities such as zooming in/out and panning, tooltips, mapping and rendering controls (such as changing the colour, the type of symbol, the level of transparency, the shadow effect, etc.). Interacting with 3D visualization of cadastre data may be 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 unit.
- 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 (Rights, Responsibilities, and Restrictions).
- 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 neighbouring 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.
- Analyse 3D spatial relationships such as 3D overlapping analysis to identify RRR conflicts.
- Support other management systems including land taxation, construction permits, urban planning, and land use regulation.

The following series of figures illustrate some of these benefits. Figure 8 shows the use of transparency to co-visualize administrative (or legal) objects and buildings and thus improve the distinction between categories of 3D objects. Figure 9 demonstrates the use of highlighting techniques such as slicing and detaching a floor to better see inside the 3D cadastral model. Figure 10 illustrates another example of highlighting techniques as one floor is detached from the 3D model while tooltip is used to present characteristics of one property unit. Figure 11 demonstrates the use of the BIM environment to model.

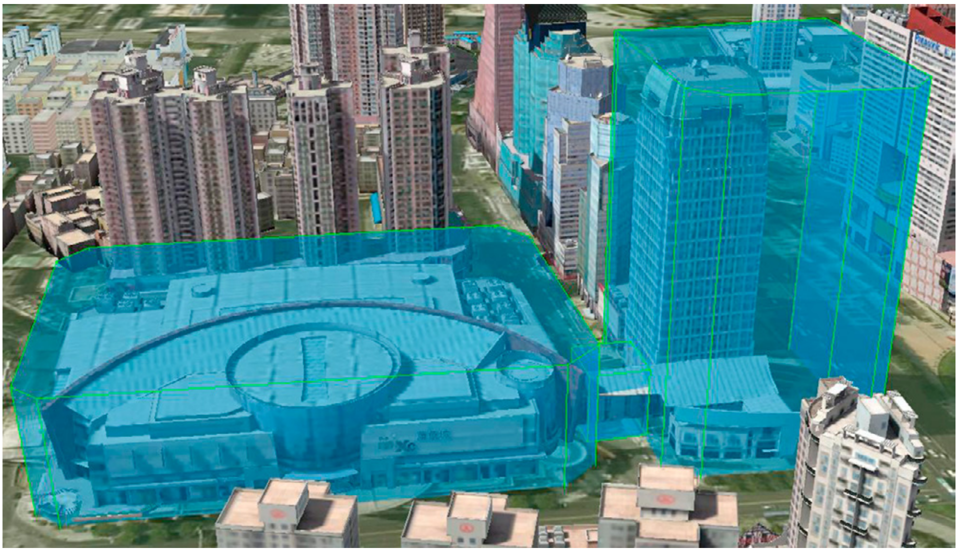

Figure 8. *Using transparency to enhance the visualization of 3D cadastre and building spaces (source Ying et al. 2012).*

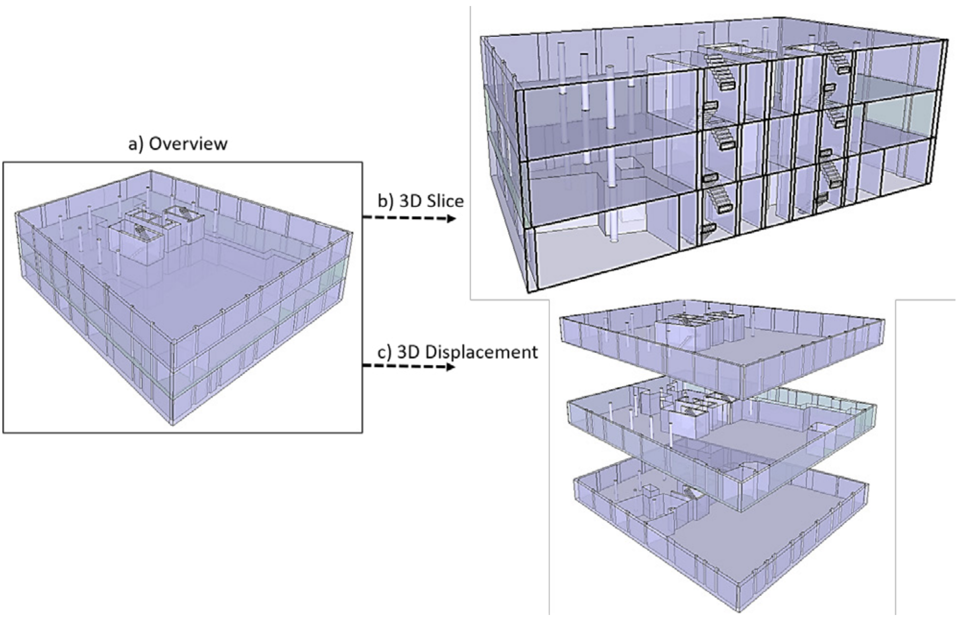

Figure 9. *Highlighting techniques applied to the visualization of three floors of an apartment (original 3D model built by group VRSB, Quebec City).*

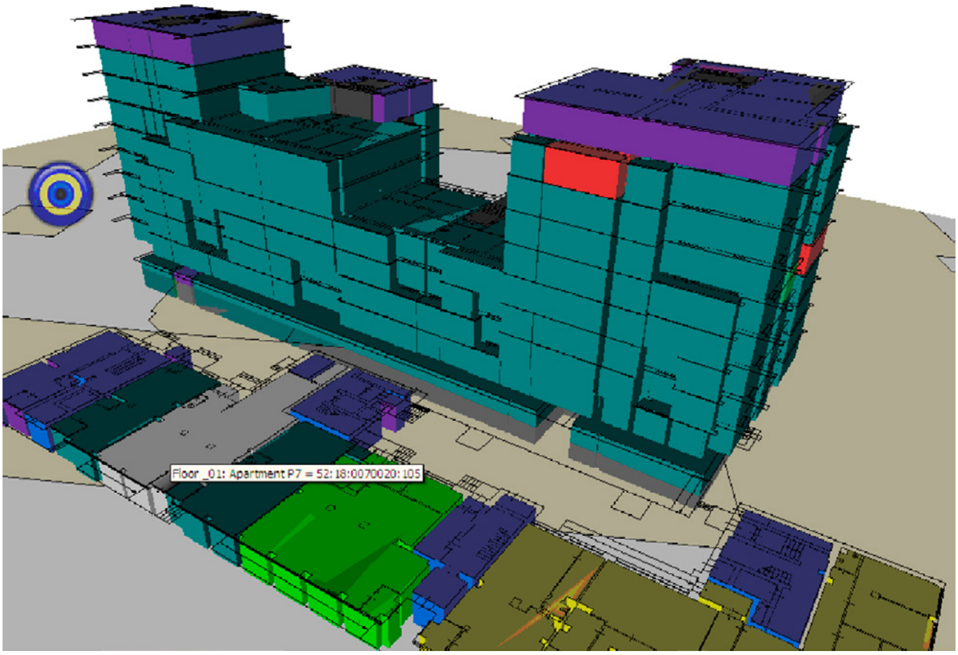

Figure 10. *Floor_01 dragged outside the building. Note the tooltip which contains the identifier of the object during move-over (apartment P7) (source Vandysheva et al. 2012).*

A legal boundary defined by the interior of walls | *A legal boundary not defined by walls*

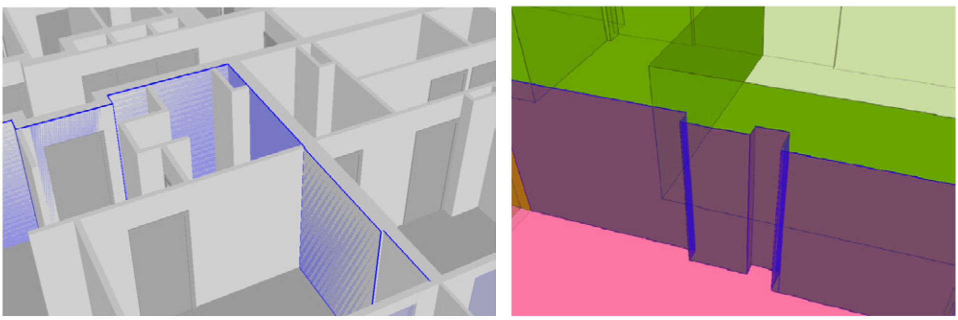

Figure 11. *BIM distinction between legal and physical boundaries (built from Atazadeh et al. 2017a+b).*

5.4 Challenges and Research Opportunities in 3D Cadastre Visualization

While having positive benefits, visualizing the third dimension in a cadastral system is by no means a solved problem, bringing challenges that include (Shojaei 2014; van Oosterom 2013; Wang 2015):

- A requirement for the user to develop skills when interacting with the 3D visualization interface, in order to be able to carry out 3D cadastral work with the same efficiency as in 2D.

- Standard, well known mapping rules applied in 2D (e.g. selecting colour schema or symbols to represent the cadastral unit) may not perform in the same way in a 3D visualization.
- 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 indetails,
  - 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, further complicates the visualization – the more features and complexity the more cognitive load, and the slower system performance.
- 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 such as unlimited air space or depth limitation.
- Visualization of 3D parcels and their temporal dimension (via animations or other techniques) is also required.
- 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.

In order to summarize the challenges introduced by 3D cadastral visualization, the following tables group them into three groups – "users and user requirements", "cadastral information and semiotic/rendering aspects", and finally "3D cadastral platforms and functionality".

Understanding users (Table 3) is perhaps the most fundamental one among all the challenges to be addressed, as it is only through this process, and through close collaboration with users, that it will 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. Impor-

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

User Groups	Requirements	Challenges
– Land Registry – Local Government – Land surveyors, Notaries, Land lawyers – Architects, Engineering and Construction – Land and urban planners – Property development – Building Management – Real Estate – General Public	– Identify 3D property – Understand the 3D geometry – Locate and compare – Measure and do spatial analysis – Control accuracy – Query geometry and attributes – 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

Table 4. *Cadastral information and semiotic/rendering aspects of 3D cadastral 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 "chains" of property rights
	– Altering and suitability of visual variables
	– Applying texture and transparency
	– Slicing, detaching, cross sections
	– Discretization and distortion
		– Legal boundaries not visible
		– Embedding within the legal decision making process
		– Availability of 3D cadastral data
		– Geometric complexity of apartments and other structures
		– Temporal data visualization

Table 5. *3D cadastre platforms and their functions in the context of cadastre visualization.*

Platforms	Functions	Challenges
– Web/desktop/mobile – 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 – 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

tantly, 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 (Table 4) 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, visualizing hidden objects, navigating in a 3D world, providing details about RRR) but also the recognition 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.

The above requirements are central to allowing cadastre users to accomplish their daily tasks. However, integrated 3D visualization tools embedding these are currently missing (Table 5), 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, many of the 3D cadastral visualization approaches have focused on ownership boundaries rather than the challenging visualization of rights 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.

In addition to the gaps highlighted above, 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.

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 system 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 as 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.

Linking the visualization system with a legal document, such as a deed or title, which is well known to cadastral experts, would help by lessening the cognitive leap required to understand the purpose of the 3D system. As a community, 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.

Having an integrated third dimension in cadastral systems brings new opportunities (Paasch et al. 2016; Rajabifard et al. 2014; Stoter 2004; Stoter and van Oosterom 2006) and 3D visualization provides a direct route to an improved understanding of 3D situations, allowing a bespoke, but familiar and more realistic, view of the world and of complex property ownership and rights and thus reducing misinterpretation. It is only by addressing 3D visualization challenges that these benefits can be achieved.

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FIG PUBLICATIONS

The FIG publications are divided into four categories. This should assist members and other users to identify the profile and purpose of the various publications.

FIG Policy Statements

FIG Policy Statements include political declarations and recommendations endorsed by the FIG General Assembly. They are prepared to explain FIG policies on important topics to politicians, government agencies and other decision makers, as well as surveyors and other professionals.

FIG Guides

FIG Guides are technical or managerial guidelines endorsed by the Council and recorded by the General Assembly. They are prepared to deal with topical professional issues and provide guidance for the surveying profession and relevant partners.

FIG Reports

FIG Reports are technical reports representing the outcomes from scientific meetings and Commission working groups. The reports are approved by the Council and include valuable information on specific topics of relevance to the profession, members and individual surveyors.

FIG Regulations

FIG Regulations include statutes, internal rules and work plans adopted by the FIG organisation.

List of FIG publications

For an up-to-date list of publications, please visit
www.fig.net/pub/figpub

ABOUT FIG

International Federation of Surveyors is the premier international organization representing the interests of surveyors worldwide. It is a federation of the national member associations and covers the whole range of professional fields within the global surveying community. It provides an international forum for discussion and development aiming to promote professional practice and standards.

FIG was founded in 1878 in Paris and was first known as the Fédération Internationale des Géomètres (FIG). This has become anglicized to the International Federation of Surveyors (FIG). It is a United Nations and World Bank Group recognized non-government organization (NGO), representing a membership from 120 plus countries throughout the world, and its aim is to ensure that the disciplines of surveying and all who practise them meet the needs of the markets and communities that they serve.

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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