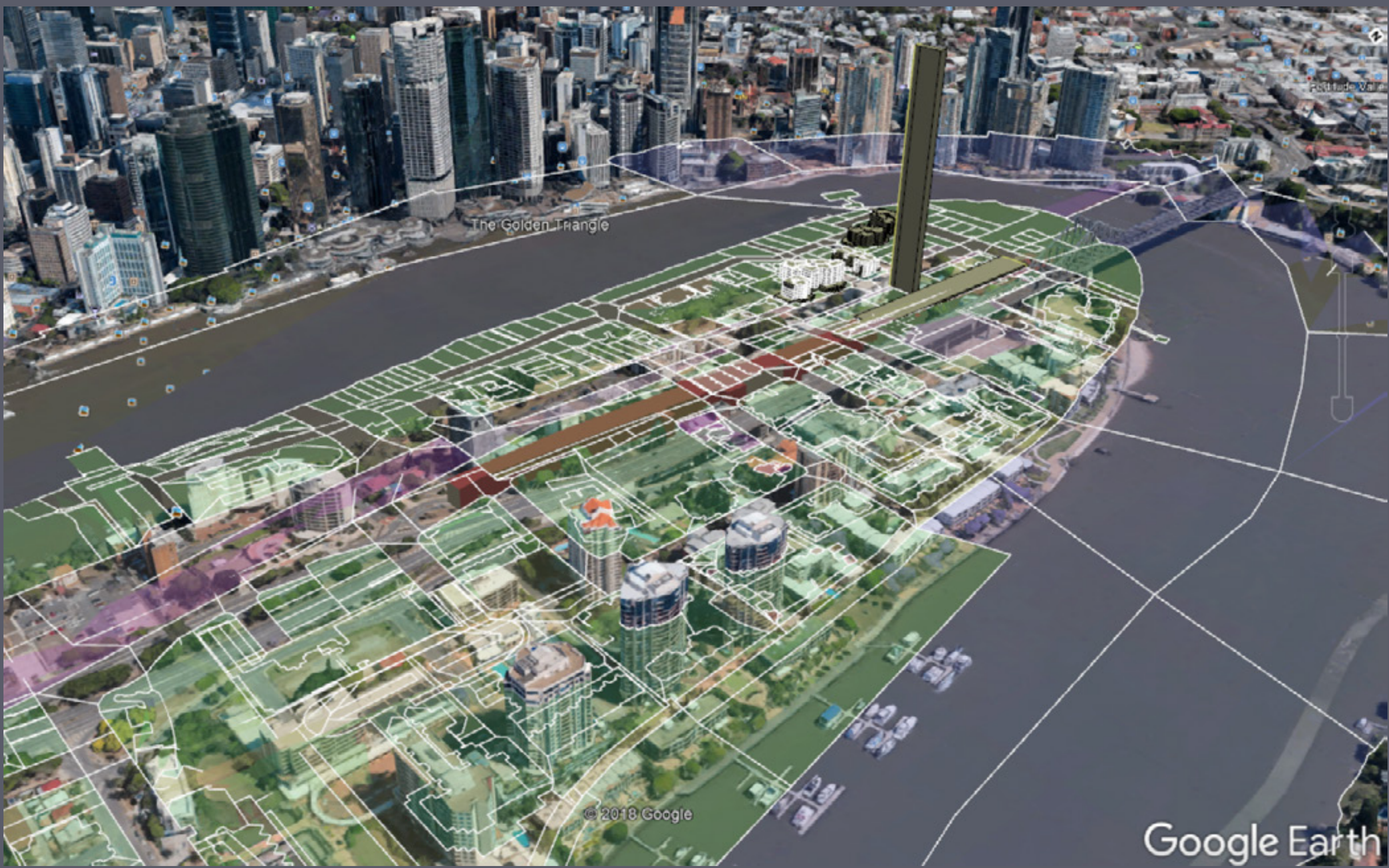
FIG publication

Best Practices 3D Cadastres

Extended version



Editor: Peter van Oosterom

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

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

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

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International Federation of Surveyors (FIG)
Kalvebod Brygge 31-33
DK-1780 Copenhagen V
DENMARK

Phone: +45 3886 1081
Fax: +45 3886 0252
E-mail: FIG@fig.net
Website: www.fig.net

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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

ORGANIZATION OF THE WORKING GROUP ON 3D CADASTRES

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

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

Argentina	Diego Alfonso Erba
Australia	Ali Aien, Don Grant, Mohsen Kalantari, Sudarshan Karki, Davood Shojaei, Rod Thompson
Austria	Gerhard Muggenhuber, Gerhard Navratil
Bahrain	Neeraj Dixit, Ammar Rashid Kashram
Brazil	Andréa Flávia Tenório Carneiro
Canada	Francois Brochu, Louis-André Desbiens, Paul Egesborg, Marc Gervais, Jacynthe Pouliot, Francis Roy
China	Renzhong Guo, Zhang Ning, Shen Ying
Costa Rica	Andres Hernández Bolaños
Croatia	Miodrag Roic
Cyprus	Elikkos Elia
Czech Republic	Karel Janecka
Denmark	Lars Bodum, Esben Munk Sørensen, Christian Thellufsen
Finland	Jani Hokkanen, Arvo Kokkonen, Tarja Myllymäki
France	Claire Galpin, Hervé Halbout
Germany	Markus Seifert
Greece	Efi Dimopoulou
Hungary	Gyula Iván, Andras Osskó
India	Tarun Ghawana, Pradeep Khandelwal
Indonesia	Trias Aditya, S. Subaryono
Israel	Yerach Doytsher, Joseph Forrai, Gili Kirschner, Yoav Tal
Italy	Diego Navarra, Bruno Razza, Enrico Rispoli, Fausto Savoldi
Kazakhstan	Natalya Khairudinova
Kenya	David Siriba
Macedonia	Gjorgji Gjorgjiev, Vanco Gjorgjiev
Malaysia	Teng Chee Hua, Alias Abdul Rahman
Nepal	Babu Ram Acharya

The Netherlands	Benedict van Dam, Christiaan Lemmen, Hendrik Ploeger, Martijn Rijsdijk, Jantien Stoter
Nigeria	Thomas Dabiri
Norway	Lars Elsrud, Olav Jenssen, Lars Lobben, Tor Valstad
Poland	Jaroslaw Bydlosz, Marcin Karabin
Portugal	José Paulo Elvas Duarte de Almeida, João Paulo Fonseca Hespanha de Oliveira, Mateus Magarotto
Russian Federation	Sergey Sapelnikov, Natalia Vandysheva
Serbia	Rajica Mihajlovic, Nenad Visnjevac
Singapore	Victor Khoo, Kean Huat Soon
South Korea	Youngho Lee
Spain	Amalia Velasco
Sweden	Peter Ekbäck, Jesper Paasch, Jenny Paulsson
Switzerland	Helena Aström Boss, Robert Balanche, Laurent Niggeler
Trinidad and Tobago	Charisse Griffith-Charles
Turkey	Cemal Biyik, Osman Demir, Fatih Döner
United Kingdom	Gareth Robson, Carsten Rönsdorf
USA	Bod Ader, David Cowen, Carl Reed, Alex Smith

Chapter 2. Initial Registration of 3D Parcels

Efi DIMOPOULOU, Greece, Sudarshan KARKI, Australia, Miodrag ROIĆ, Croatia, José-Paulo Duarte de ALMEIDA, Portugal, Charisse GRIFFITH-CHARLES, Trinidad and Tobago, Rod THOMPSON, Australia, Shen YING, China, Jesper PAASCH, Sweden and Peter van OOSTEROM, The Netherlands

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

SUMMARY

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

1. INTRODUCTION

1.1 Background

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

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

1.2 The need for 3D parcel registration

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

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

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

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

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

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

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

2. CURRENT STATUS OF 3D REGISTRATION

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

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

2.1.1 China

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

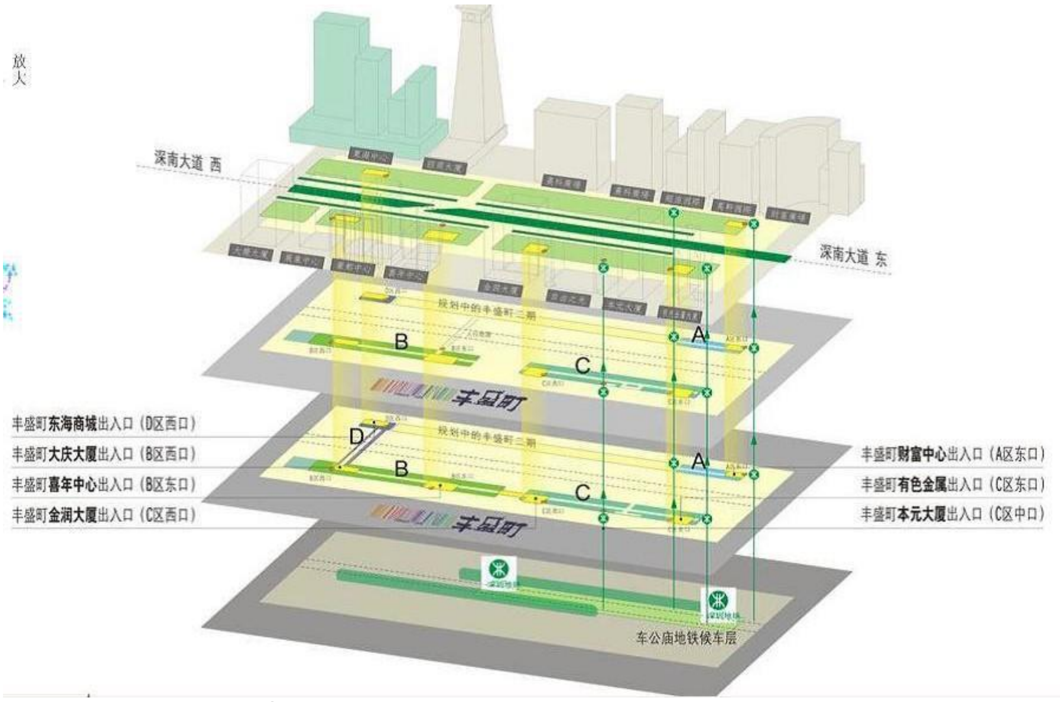


Figure 1. 3D land use of pure 3D underground space

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

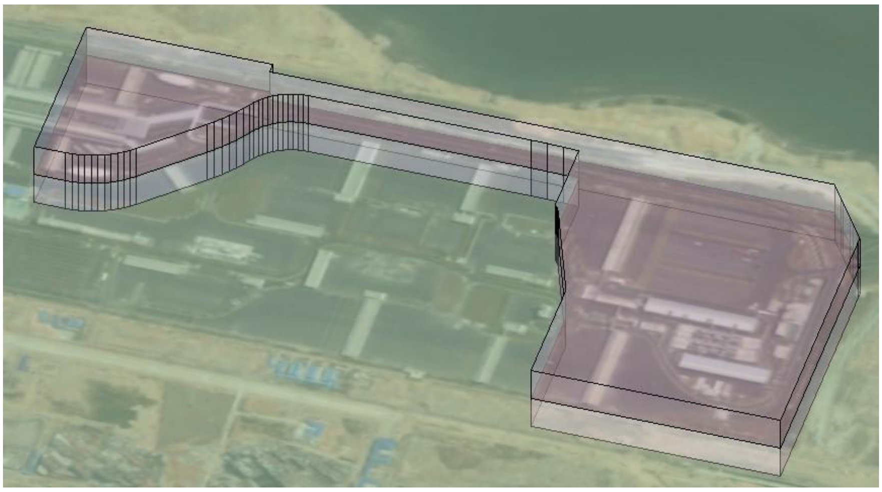


Figure 2. 3D space with multiple jurisdictions in Shenzhen Bay Port area

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

2.1.2 Croatia

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

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

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

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

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

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

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

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

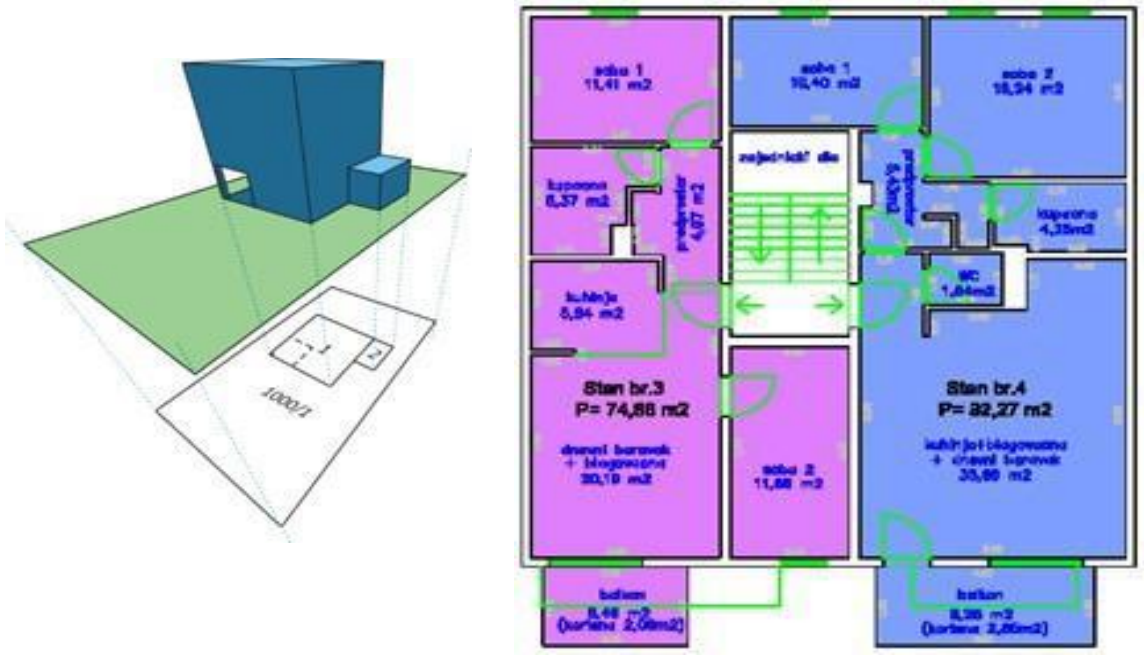


Figure 3. Property on the cadastral map and presentation of parts (separate and common) per floor

2.1.3 Greece

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

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

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

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

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

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

2.1.4 Portugal

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

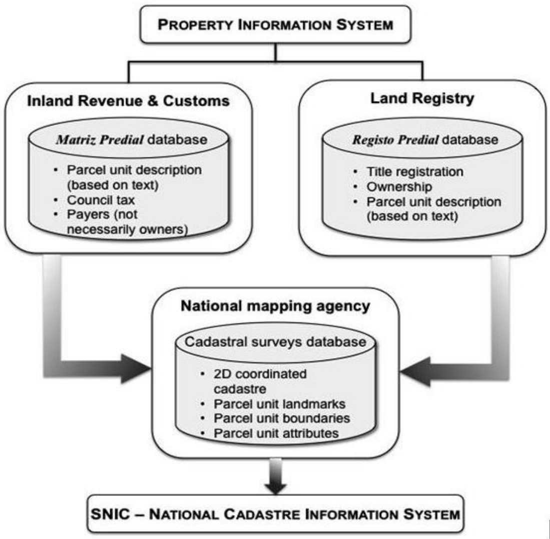


Figure 4. Overview of the current property information system in Portugal

2.1.5 Sweden

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

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

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

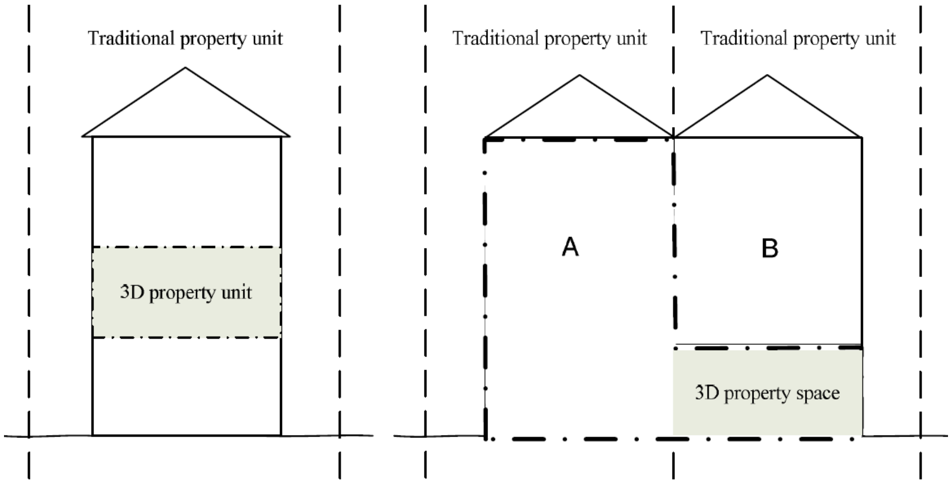
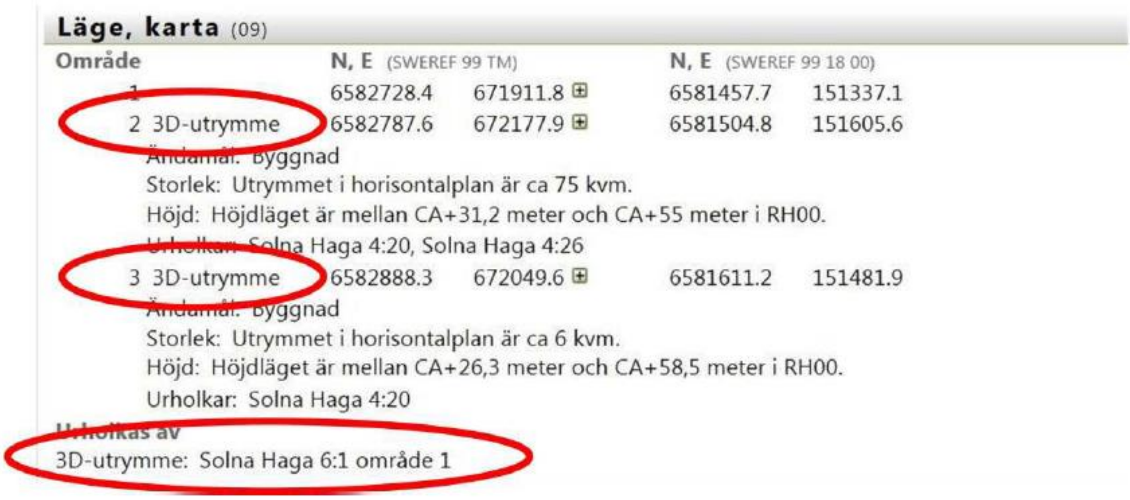


Figure 5. 3D property unit and 3D property space (Paulsson, 2012)

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

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



Läge, karta (09)

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

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

3 3D-utrymme	6582888.3	672049.6	6581611.2	151481.9

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

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

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

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

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

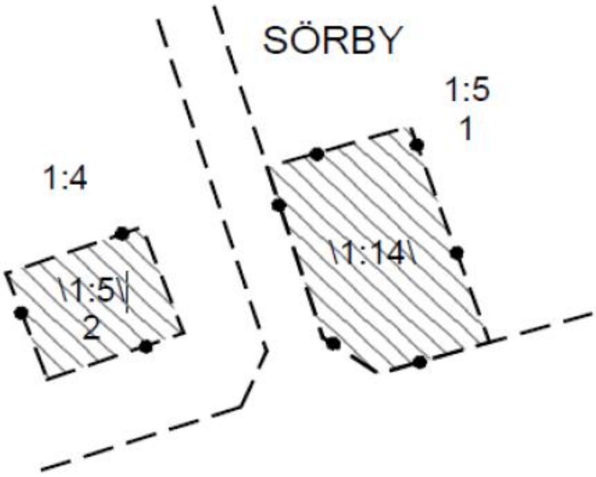


Figure 7. Cartographic representation of 3D property in the cadastral index map

2.1.6 The Netherlands

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

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

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

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


Figure 8. Impression of the 'Spoorzone Delft' project

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

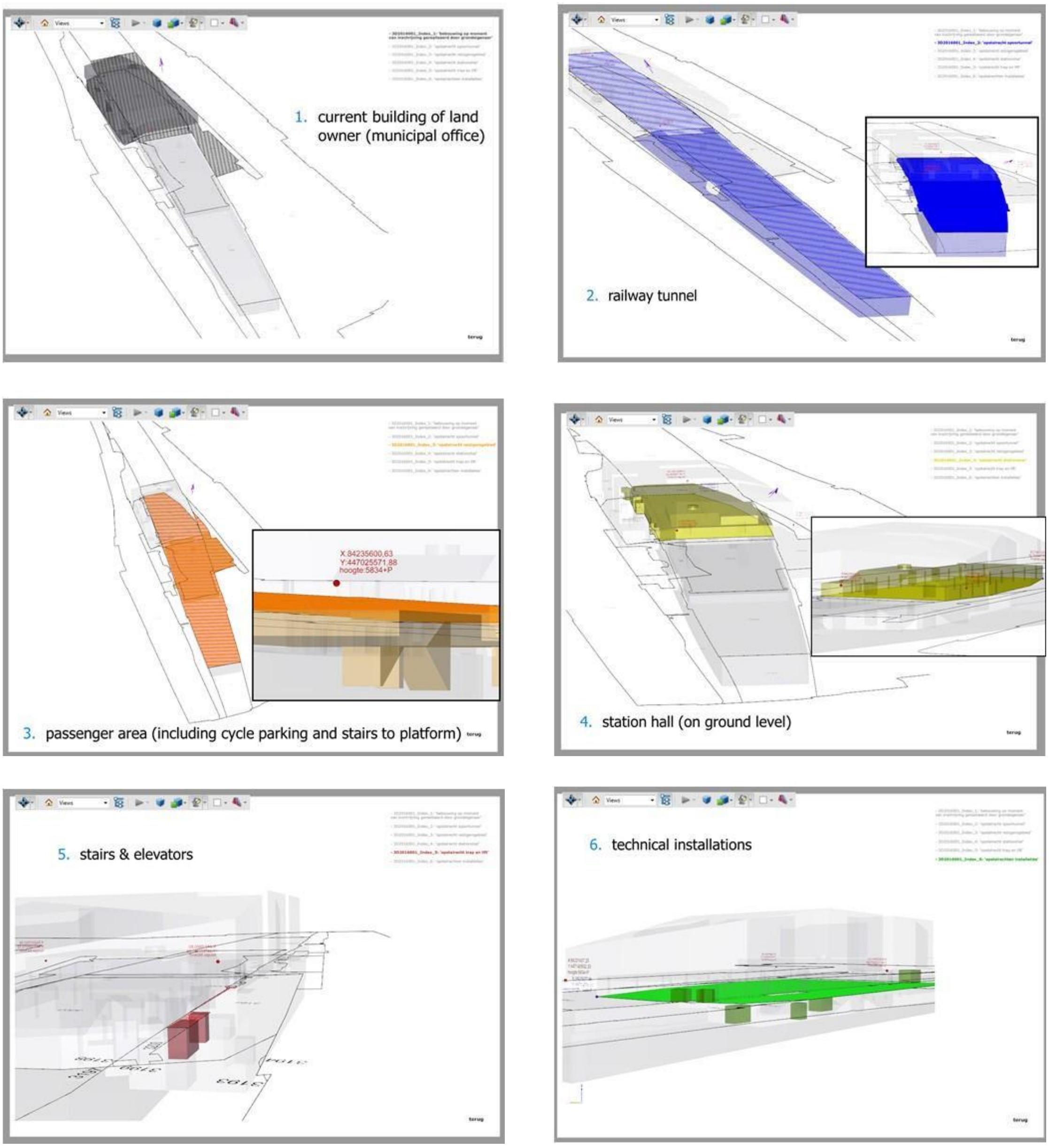


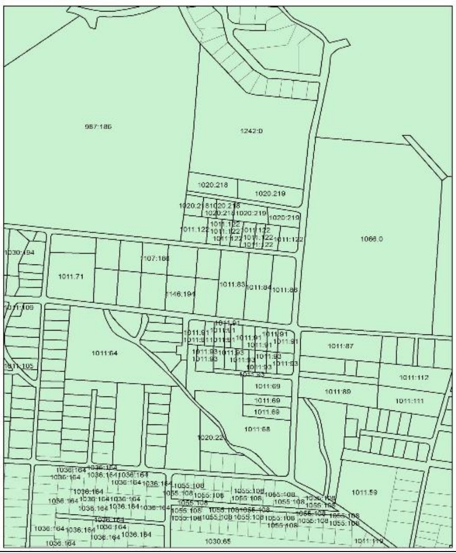
Figure 9. The six legal volumes described in the 3D pdf in land register

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

2.1.7 Trinidad and Tobago

A cadastre provides a description of the extent and nature of rights, restrictions, and responsibilities held in land, broadly defined to include earth, water, and artificial structures positioned in or on either earth or water. Where verbal descriptions are inadequate to precisely

and unambiguously define or redefine the land that is the subject of a transaction of sale, mortgage, or transfer, graphic descriptions become necessary. In some instances 2D graphic descriptions are adequate but when these do not suffice, 3D and 4D graphic descriptions become important. The economic or social benefit of having a 3D or 4D cadastre must outweigh the costs of establishing the system. This is particularly so for developing countries such as Trinidad and Tobago.
The Cadastre in Trinidad and Tobago is currently incomplete and out of date. Digital data exists of 200,000 parcels as shown in Figure 10, but thousands of plans have been scanned but not yet added to the Cadastre. Cadastral survey plans continue to be submitted in hardcopy and this further restricts the speed of updating of the cadastre. The cadastre is a digital index of uncoordinated surveys that provides information on the location of the field survey plans. However, because of the cadastre’s lack of currency, searches for information can become frustrating or, at worst, futile. There is no unique parcel identifier that can assist with this search and addresses are non-standardized although a new initiative is attempting to rectify this latter issue with a proposed zip coding. Parcels are defined and redefined relative to the surrounding parcels and their boundaries, which are marked at the turns by boundary irons. Coordinates, therefore, have no legal standing.
There are no immediate plans to transition the existing 2D cadastre to a 3D cadastre as there is much rationalization of the existing data to perform first. In the meantime, strata (condominium) rights are indicated in vertical sections in insets on the 2D cadastral plans (see Figure 11), and subsurface reserves and mining rights are shown on 2D plans related to the surface parcels. The location of these 3D properties are not visualized on the 2D cadastre, but the physical buildings can be seen on the underlying topographic imagery, which is current to 2015 as shown in Figure 12a. No elevations are recorded on these plans to a standard datum but heights relative to the ground can be included in the vertical sections.



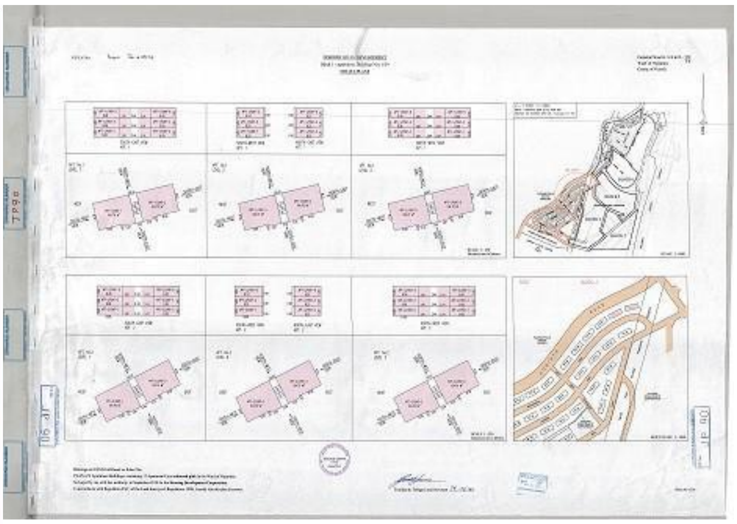


Fig. 10. Trinidad and Tobago’s digital 2D cadastre Fig.11 Vertical sections on survey plans depict 3D rights

The individual parcels in the graphical cadastre are also not linked to the registered deeds and titles containing information on interests that are located at the legal registry of the Registrar General’s Office. Rights, restrictions and responsibilities are therefore not graphically

displayed in the cadastre but some may be expressed textually in the deed document at the registry. Urban and regional development plans are held at a separate state institution, they are approximate in definition of extent, and are not linked to the cadastre. There is no fiscal cadastre as the valuation rolls are manual and contain no graphics. The majority of registered interests are deeds based with a small minority being supported by title registration. The cadastre does not show the level of interest but solely the extent of the interest. While all title documents refer to or contain a graphical description of the parcel in a survey plan, many deeds that date back several decades do not contain a survey plan but a verbal description of the parcel referring to adjoiners which no longer exist. A recent project upgraded the Cadastral Management Information System (CMIS) which includes the procedure for receiving new cadastral plans, checking and approving them, and entering them on the database. As part of this project, new software was installed that speeds up the maintenance of the cadastre, however the limited human resource is still an issue that can restrict this progress.
The description of the rights themselves is done textually in the deed document, the rights to the individual condominium being expressed as a share in a company possessing the entire property. 3D registration therefore occurs when the deed is prepared that reflects that a transaction of a percentage of shares, representing a parcel shown in a graphical cadastral plan attached, has occurred. This demonstrates that 3D cadastres can be manual and represented in 2D space similar to how 3D digital cadastres are reflected in 2D space but visualized in 3D. The legislation in Trinidad and Tobago gives the authority to the land surveying profession and the Director of Surveys to make rules for the graphic description of any rights held in land (Griffith-Charles and Edwards, 2014).
Trinidad and Tobago is therefore at a more rudimentary level of physical 3D registration, graphically recording only those 3D physical spaces that are in condominiums with the use of 2D plans with vertical sections describing the third dimension. While Griffith-Charles and Sutherland (2013) analyze the costs and benefits of instituting a 3D cadastre in Trinidad and Tobago, and suggest only partial and primarily urban implementation, the current weakened economy discourages a full scale launch into its establishment. Full coverage LiDAR data taken over the country in 2015 as shown in Figure 12b, which can support the development of a visualization of the physical cadastral boundaries where they intersect with the conceptual cadastral boundaries.

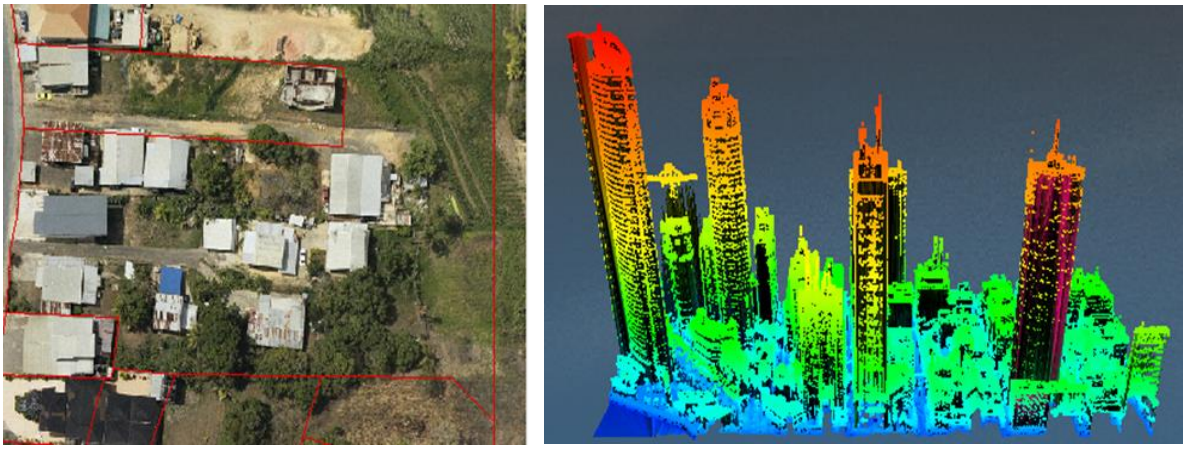


Figure 12 (a) Orthophotography indicates topography related to the cadaster (b) LiDAR data of urban Trinidad and Tobago

2.2 Comparison between the presented countries

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

Table 1: Summarizing common characteristics and differences

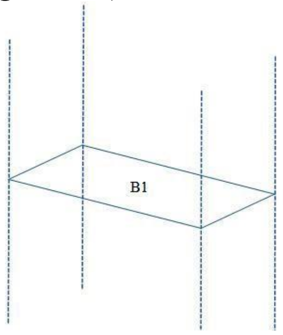
COUNTRY	REGISTRATION SYSTEM	LEGAL PROVISION FOR 3D PARCEL REGISTRATION	BASIC UNIT FOR 3D OBJECTS	EXISTING CADASTRAL DATA SOURCES
CHINA	Titles registration system Not unified system	Yes	3D real property unit	- Land Register and cadastral map (for several cities in digital format) - 3D pilot Cadastres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

2.3 Analysis of categorisations and approaches to 3D spatial units

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

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

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



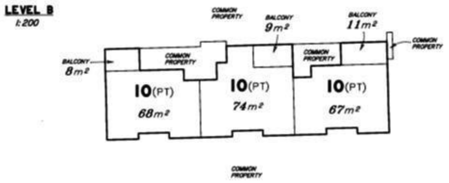
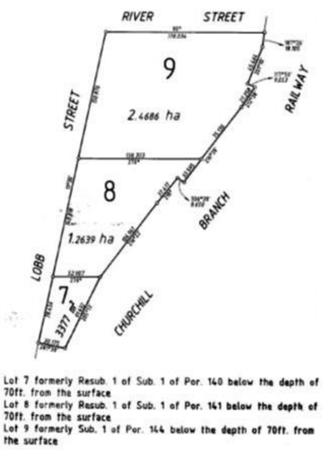


Figure 12. (a) (Left) 2D spatial unit, (b) (Right)/spatial units defined by the structure (the buildings walls)

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



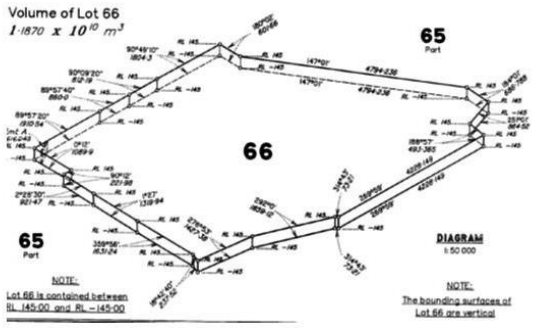


Figure 13. (a) (Left) Below the depth of spatial units, (b) (Right) A (very large) simple slice

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

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

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

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

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

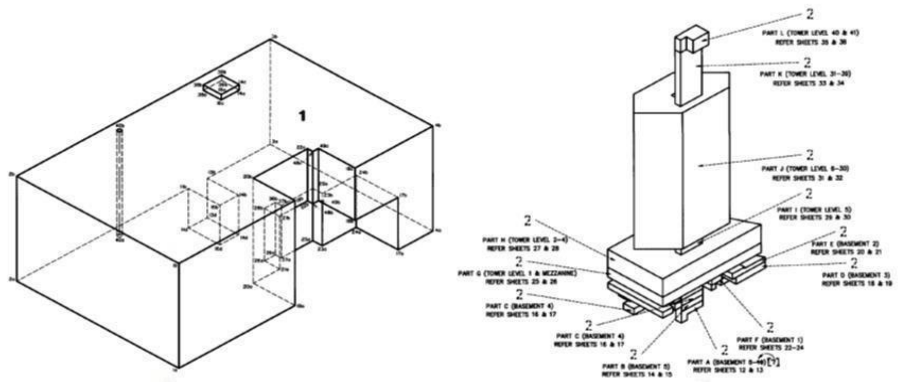


Figure 14. (a) (Left) a single-valued stepped slice, (b) (Right) a multi-valued stepped slice

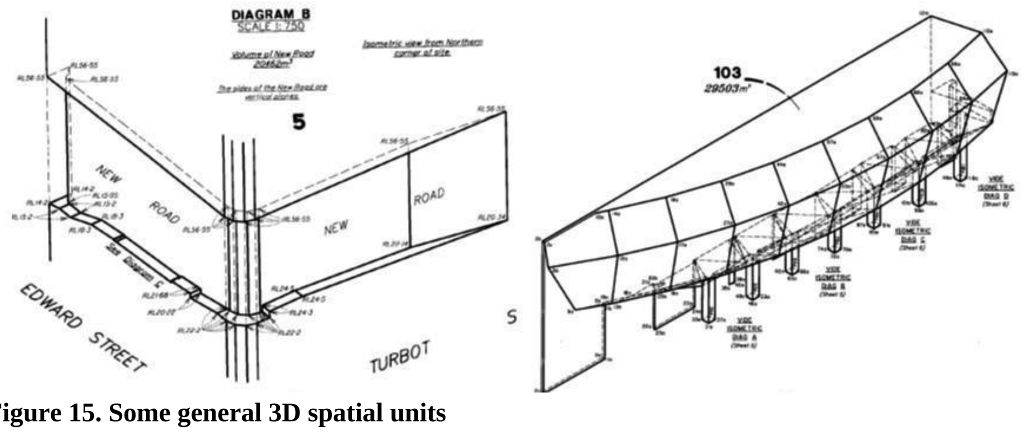


Figure 15. Some general 3D spatial units

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

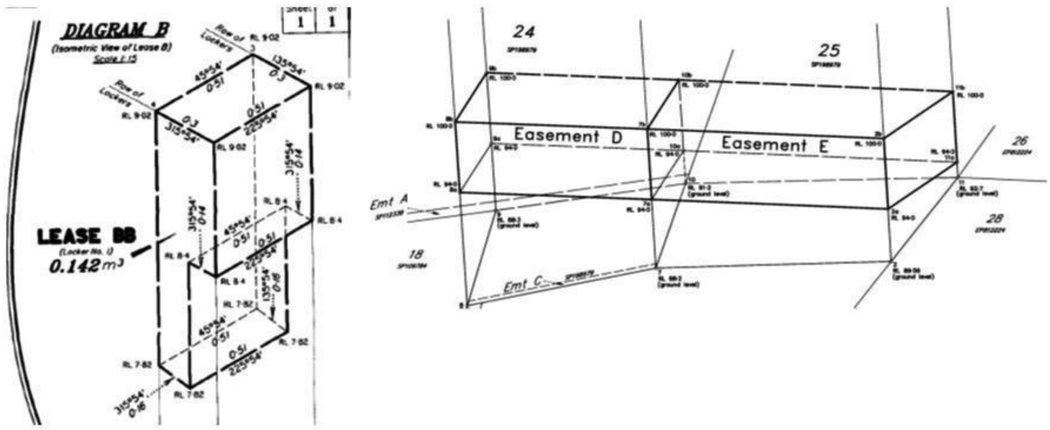


Figure 16. (a) (Left) a small lot excised from a much larger 2D spatial unit (a golf course), (b) (Right) 3D easement within 2D parcel (but this is not excised)

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

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

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

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

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

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

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

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

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

3. LEGAL AND TECHNICAL ISSUES

3.1 Sources of 3D data

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

3.2 Legal issues

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

3.2.1 Legal objects

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

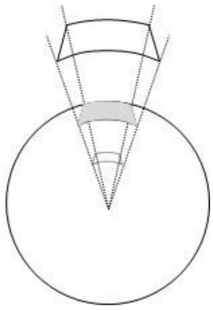


Figure 17. Legal object

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

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

3.2.2 Registration of legal objects

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

3.3 Technical Issues

3.3.1 Data submission and validation

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

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

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

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

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

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

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

linked table or location.
Specifically:

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

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

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

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

4. CONCLUSIONS AND FUTURE TRENDS

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

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

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

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

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