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3D CADASTRE – A MOTIVATION AND RECENT DEVELOPMENTS OF TECHNICAL ASPECTS

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Abstract:

The paper gives motivation for considering a 3D cadastre based on the registration of 3D spatial units, i.e. the (bounded) amount of space to which a person is entitled by means of real right. This approach gives a better insight into the registration of rights and restrictions. In 2012 the international standard ISO 19152 Land Administration Domain Model (LADM) was approved. The LADM is a conceptual model, its purpose is not to replace the existing systems, but rather to provide a formal language for describing them, so that their similarities and differences can be better understood and it also offers the concepts for the modelling of 3D spatial units. Based on the LADM, country profiles can then be defined and extended. The paper further explores the technical aspects of a 3D cadastre, especially summarizing the main findings and challenges in 3D information modelling and 3D spatial databases for a 3D cadastre.

Keywords: ISO 19152 LADM, 3D spatial units, technical aspects of 3D Cadastre.

3D KATASTAR – MOTIVACIJA I TRENUTNA DOSTIGNUĆA TEHNIČKIH ASPEKATA

Apstrakt:

Ovaj rad daje motivaciju za razmatranje 3D katastra zasnovanog na registraciji trodimenzionalnih prostornih jedinica, tj. (ograničenog) prostora na koji pojedinac ima stvarno pravo. Ovaj pristup daje bolji uvid u registraciju prava i ograničenja. 2012. godine je odobren međunarodni standard modela upravljanja zemljištem ISO 19152 (LADM). Model upravljanja zemljištem (LADM) je konceptualni model, njegova svrha nije da zamijeni postojeće modele, već da obezbijedi formalni jezik za njihovo opisivanje, tako da se njihove sličnosti i razlike mogu bolje razumijeti. Takođe, on pruža i koncepte za modelovanje trodimenzionalnih prostornih jedinica. Na osnovu modela LADM, nacionalni modeli mogu biti definisani i prošireni. U radu se dalje istražuju tehnički aspekti 3D katastra, posebno sumirajući glavna otkrića i izazove u 3D modelovanju informacija i 3D prostornim bazama podataka za 3D katastar.

Ključne riječi: ISO 19152 LADM, 3D prostorne jedinice, tehnički aspekti 3D katastra

1. INTRODUCTION

The cadastre is a source of information serving for protection of rights to real estates, for tax and fees purposes, for environmental, agriculture and forest land protection, for protection of natural resources, cultural monuments, for urban planning, for evaluation of real estates, for scientific, economical and statistical purposes so as for creation of further information systems. The challenge is how to register the 3D situations (e.g. overlapping constructions) in the cadastre which is usually based on 2D parcel paradigm. Due to the increasing number of people living especially in big cities and pressure on the use of the land in such areas the amount of these 3D situations is still growing. Therefore the change of paradigm from the traditional cadastre based on 2D parcel towards the 3D cadastre based on the registration of 3D property unit should be considered. The definition of 3D cadastre is given in [1]: A 3D cadastre is a cadastre that registers and gives insight into rights and restrictions not only on parcels, but also on 3D property units. A 3D property unit is that (bounded) amount of space to which a person is entitled by means of real rights.
The main factors for considering the 3D cadastre are: a considerable increase in (private) property values, the number of tunnels, cables and pipelines, underground parking places, multilevel buildings and also an upcoming 3D approach in other domains (e.g. 3D Geographical Information Systems) which makes a 3D approach of cadastral registration technologically realizable [2]. When talking about the building of the 3D cadastre, the legal, organizational and technical aspects need to be addressed. This paper focuses on the technical aspects, especially on summary of the recent developments of the 3D information modelling and 3D spatial databases for 3D cadastres.
The rest of the paper is structured as follows: the section 2 gives the examples of situations which is hard to register using 2D parcels. It is obvious that using 3D spatial units (3D property units) would give better insight into these 3D cadastral situations. The section 3 introduces the international standard ISO 19152 Land Administration Domain Model [3] which supports the registration of 3D RRR (right, restrictions and responsibilities) using 3D spatial units and section 4 then presents the LADM based country profiles. The recent development of technical aspects of 3D Cadastres are described in the section 5. The section 6 concludes the paper.

2. MOTIVATION FOR 3D CADASTRE

In the last decades the number of 3D situations (which also need to be registered in the cadastre) is increasing. [2] defines these 3D situations as situations in which different property units (with possibly different types of land use) are located on top of each other or constructed in even more complex structures. The examples of such 3D situations are given in this chapter and also their registration in 2D cadastre based on 2D parcels is demonstrated. Figure 1 displays the situation when one construction (an apartment building) is partially located above the other construction (a restaurant) and the way in which this 3D situation is depicted on the valid 2D digital cadastral map.

Figure 1. (up left) At first sight one could say that there are two tall buildings and one smaller standing between them. (up right) In fact, there is a building (highlighted in blue), which is partially located above the other building (highlighted in green). (down) The 3D situation depicted on the 2D cadastral map in combination with orthophoto.

The figure 2 introduces a general principle how the untypical constructions are displayed in 2D cadastral map. It can be easily recognized that the footprint does not provide user with information about the whole extent of legal space to which the owner’s rights are attached.

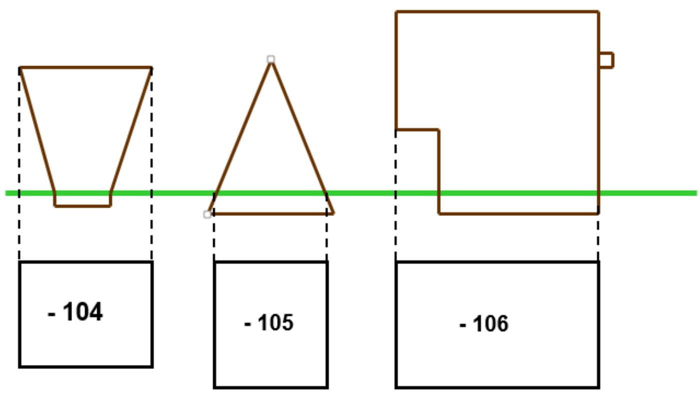

Figure 2. Visualization of the untypical building in the 2D cadastral map [4].

Another example of the typical 3D situation gives fig. 3. There are buildings over public roads.

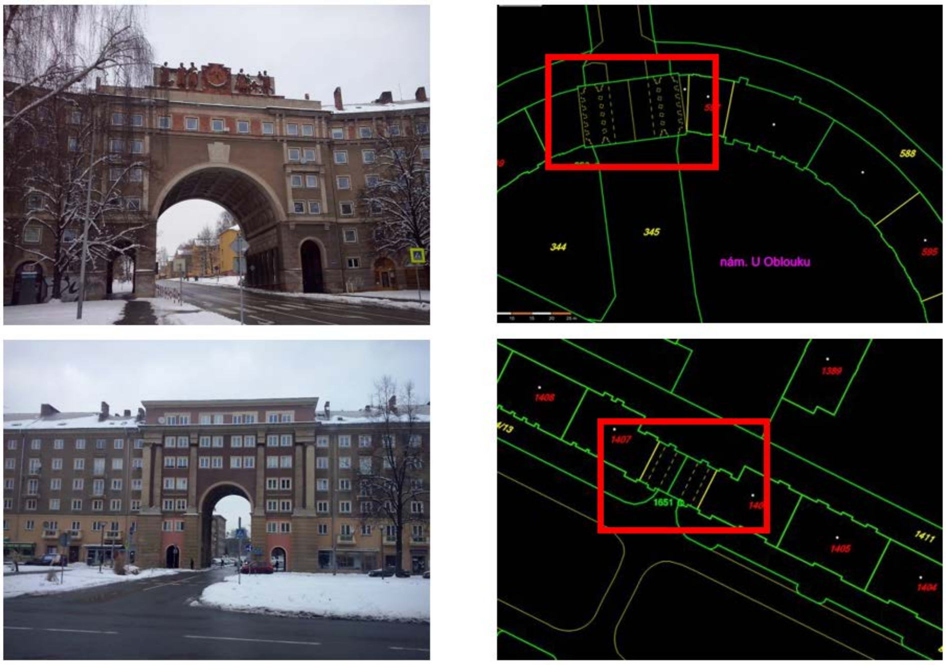

Figure 3. Buildings (left column) and their portrayal in existing 2D digital cadastral map (right column). On the cadastral map one can see only the outlines of the building (on the surface level).

In the cadastre, also the underground constructions should be registered. Figures 4 and 5 demonstrate the principle how the underground constructions are displayed in existing 2D cadastre in the Czech Republic. Recently several studies have examined how the underground constructions could be registered in 3D cadastre [5, 6].

Figure 4. (left) Visualization of the underground construction of the archeological park in Pavlov [4]; (right) Entrance to the archeological park in Pavlov (photo: Institute of Archeology of the CAS, Brno).

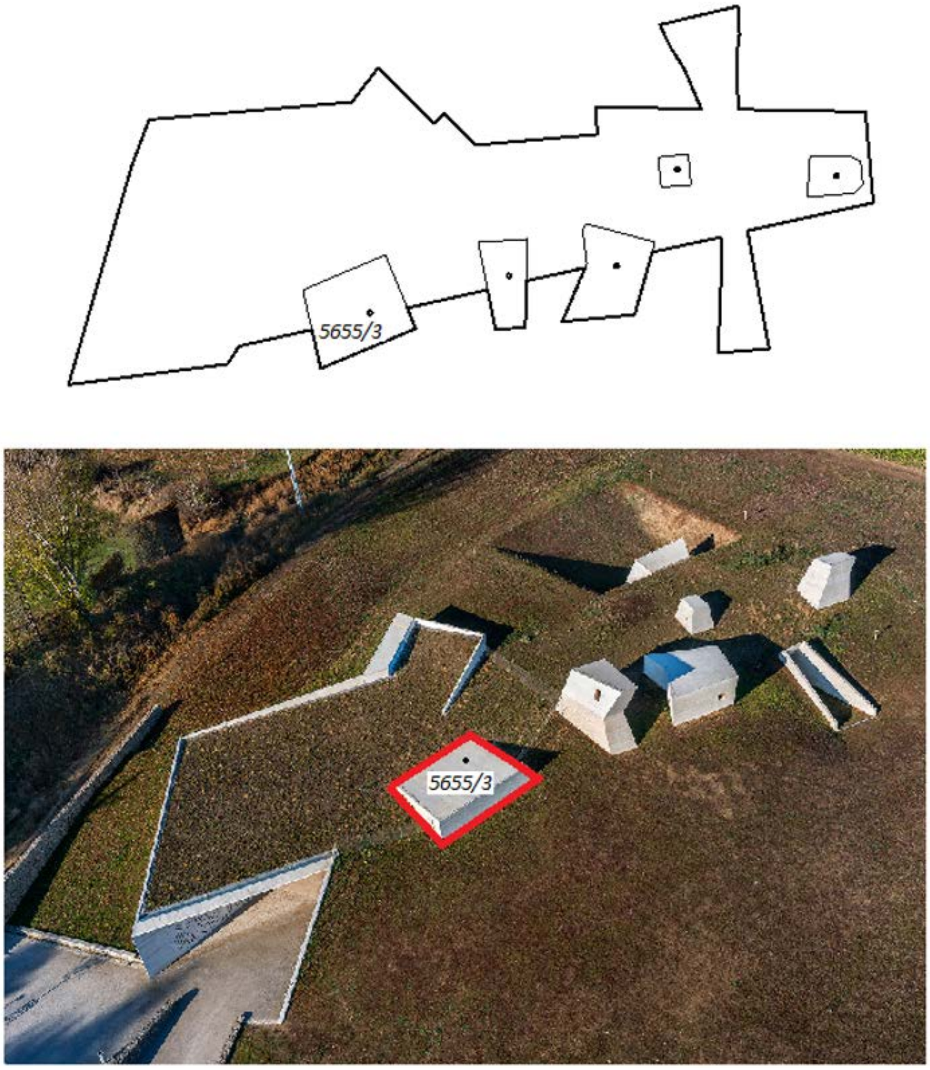

Figure 5. 2D visualization of the boundaries of underground construction (Archeological park Pavlov, Czech Republic) on the cadastral map. Every component of the construction located above ground is displayed on a "separate" building parcel. However, in fact, only one building parcel is registered in the cadastre (here with parcel number 5665/3). (down) The photography of the underground object with components located above the ground. Highlighted in red is the part of the underground object corresponding to the building parcel 5655/3 (source of photography: http://alesjungmann.cz/project/archeopark-pavlov).

3. MOTIVATION FOR 3D CADASTRE

This International Standard [3] defines the Land Administration Domain Model (LADM). The LADM is a conceptual model. The purpose of the LADM is not to replace existing systems, but rather to provide a formal language for describing them, so that their similarities and differences can be better understood. LADM is a descriptive standard, not a prescriptive standard. The LADM provides a reference model which will serve two goals:

- to provide an extensible basis for the development and refinement of efficient and effective land administration systems, based on a Model Driven Architecture (MDA), and
- to enable involved parties, both within one country and between different countries, to communicate, based on the shared vocabulary (that is, an ontology), implied by the model.

The LADM:

- defines a reference Land Administration Domain Model covering basic information-related components of land administration (including those over water and land, and elements above and below the surface of the earth);
- provides an abstract, conceptual model with four packages related to
    - parties (people and organizations);
    - basic administrative units, rights, responsibilities, and restrictions (ownership rights);
    - spatial units (parcels, and the legal space of buildings and utility networks);
    - spatial sources (surveying), and spatial representations (geometry and topology);
- provides terminology for land administration, based on various national and international systems, that is as simple as possible in order to be useful in practice. The terminology allows a shared description of different formal or informal practices and procedures in various jurisdictions;
- provides a basis for national and regional profiles; and
- enables the combining of land administration information from different sources in a coherent manner.

The LADM offers two concepts for modelling the 3D spatial units. In terms of LADM, 3D spatial unit is a single volume (or multiple volumes) of space. These concepts are the boundary face string concept (figure 6) and boundary face concept (figure 7).

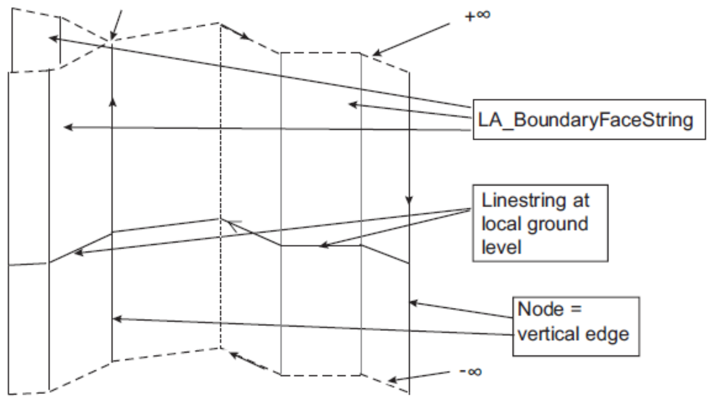

Figure 6. Boundary Face String Concept [3].

Boundary face string is a boundary forming part of the outside of a spatial unit. Boundary face strings are used to represent the boundaries of spatial units by means of line strings. In a 3D land administration system it represents a series of vertical boundary faces where an unbounded volume is assumed, surrounded by boundary faces which intersect the Earth’s surface.

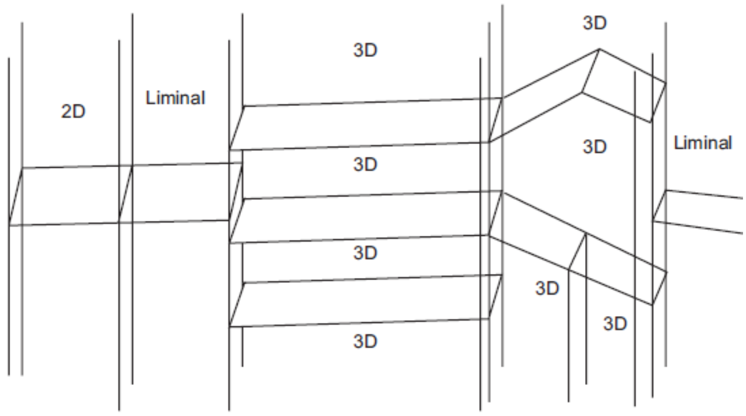

Figure 7. Side view showing the mixed use of boundary face strings and boundary faces to define both bounded and unbounded 3D volumes [3].

Boundary face is a face that is used in the 3-dimensional representation of a boundary of a 3D spatial unit. Boundary faces are used when the implied vertical and unbounded faces of a boundary face string are not sufficient to describe 3D spatial units. Boundary faces close volumes in height, or in depth, or in all directions to form a bounded volume. The volumes represent legal spaces.

4. LADM-based country profiles

The ISO 19152 Land Administration Domain Model (LADM) is regarded as a conceptual model that enforces certain relationships between the entities. To test the compliance between the LADM and the national data cadastre model, it is necessary that an application scheme (i.e., a country profile) is developed.

On principle, there are three main ways in which the LADM based country profile can be developed: (1) use LADM classes, attributes, codelists and relationships between classes “as is”, (2) show an inherited structure between the LADM and the existing cadastral model, or (3) show a mapping of elements between LADM and the existing cadastral model. The last two approaches were used for the creation of the LADM based country profiles for example in Croatia [7], Czech Republic [8], see figure 8, Poland [9], and Serbia [10]. In all these mentioned countries the cadastre is currently based on registration of 2D parcels.

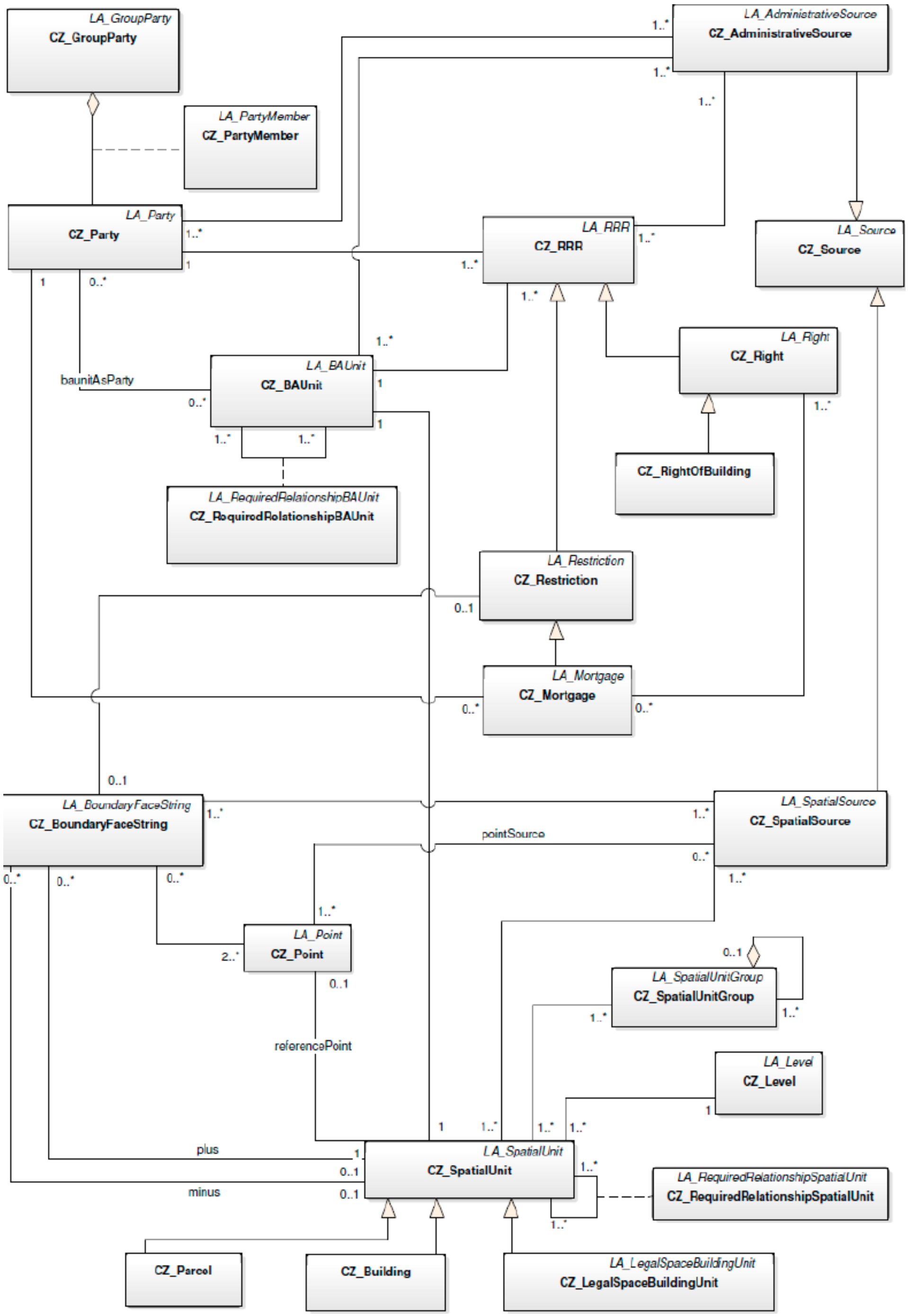

Figure 8. The Czech LADM-based country profile [8].

LADM allows for registration of 3D parcels and recently several prototypes of 3D LADM based country profiles have also even been developed, for example: Russian Federation

[11], Poland [12], Malaysia [13, 14], Israel [15], Greece [16], Trinidad and Tobago [17] or Turkey [18].

5. RECENT DEVELOPMENTS OF TECHNICAL ASPECTS OF 3D CADASTRES

5.1. 3D CADASTRAL INFORMATION MODELLING

The various aspects of 3D Cadastral Information Modelling need to be addressed, e.g. the possibilities of linking 3D legal right, restriction, responsibilities (RRR) spaces, modelled with LADM, with physical reality of 3D objects (described via CityGML, IFC, InfraGML, etc.). This is closely related to the legal framework and initial registration of 3D spatial units (3D parcels).

An initial categorization of 3D parcels was given in [19] 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 .
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, as depicted in figure 9.

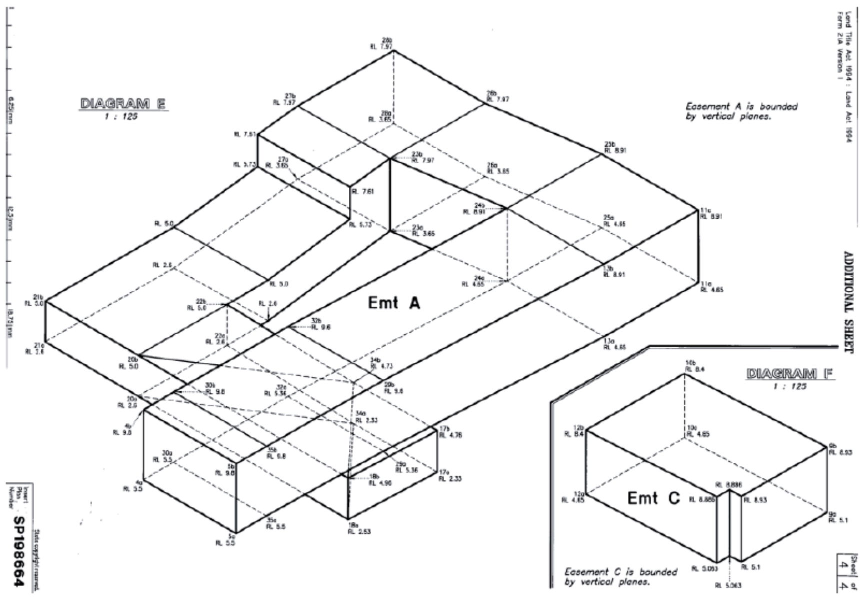

Figure 9. A general 3D spatial unit [19].

Cadastral data models, (e.g. Land Administration Domain Model (LADM)), including the 3D support, have been developed for legal information modelling and management purposes without providing correspondence to the object's physical counterparts. Building Information Models (e.g. BIM/IFC) and virtual 3D topographic/ city models (e.g. LandXML, InfraGML, CityGML, IndoorGML) are used to describe the physical reality. The main focus of such models is on the physical and functional characteristics of urban structures [20]. 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 maximize their utility and flexibility to support different applications. A model driven architecture (MDA) approach, including the formalization of constraints is the preferred. In the Model Driven Architecture (MDA) design approach as proposed by the Object Management Group (OMG) 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) is then transformed into Platform-Specific Model (PSM). This could be a relational database schema for a spatial DBMS, or XML schema for a data exchange format or the structure of maps, forms and tables as used in the graphic user interface (GUI) of a spatial application. Constraints have been proved effective in providing solutions needed to avoid errors and enable maintenance of data quality; thus the need to specify and implement them is vital [21].

How to create and maintain valid 3D parcels is still a challenge in practice [22]. At least three aspects should be clearly developed in order to manage the 3D parcels correctly [22]: (1) precise geometric models that describe the shapes and geographic locations of various 3D parcels based on flat faces; (2) volumetric or solid models that indicate boundary faces with orientation to present the corresponding 3D parcel objects; and (3) the topological relationships that encode the information about adjacencies between 3D parcels, using shared common faces/edges to preserve the consistency of the objects' geometries and support spatial query and management.

5.2. 3D SPATIAL DATABASES FOR 3D CADASTRES

Constructing 3D data models and their topological relationship are two important parts of 3D cadastre [23]. 3D Spatial Systems should then enable [24]:

- data model to handle a variety of 3D objects,
- data quality control,
- geo-referencing,
- comprehensive location based search and analysis,
- handling level of detail for seamless operation,
- high performance dissemination of 3D data,
- support high performance real-time 3D rendering,
- support for 3D standards.

Although a lot of work has been completed on defining a 2D or 3D vector geometry in standards by the OGC and the ISO, it is still insufficient to define 3D cadastral objects. 3D objects have a more rigorous definition for cadastral purposes. For a volumetric 3D cadastral object, for example, the polyhedron needs to satisfy characteristics such as closeness, interior connection, face construction and proper orientation. The LADM addresses many of the issues in 3D representation and storage of 3D data in a DBMS. It allows in-row storage of 3D data in a mixed 2D-3D database allowing for fast retrievals and analysis; it allows for 3D data to be stored in different levels of detail, overlapping 2D footprint of 3D objects, and supports liminal parcels, as well as allows attribution of different boundary lines and faces. However, an identified issue is the duplication of definition of boundaries for separate spatial units. Three-dimensional objects can be represented using voxels (volumetric pixels) as it brings advantages in object representation, object count and volume, 3D operations and simple analysis, better representation of the various levels of detail of a 3D city model, and representing 3D as a solid instead of point, line and polygon. The challenges to this are the storage and efficient handling by current spatial databases, although there are GIS systems that are working towards creating a column store structure to accommodate voxels. 3D objects can also be represented as a point cloud. LiDAR point clouds could assist to either be a reference framework of as-constructed features, or a 3D data acquisition tool for 3D physical objects, or a verification tool for pre-existing BIMs or other models. Point cloud data can be for data such as administrative, vector, raster, temporal etc. and a generic DBMS should be able to combine these data for a point cloud data type with characteristics such as xyz values, attributes per point, spatially coherent data organisation, efficient storage and compression, data pyramid support for multi-scale or vario-scale support, temporal support, query accuracy over a range of dimensions, analytical functions and parallel processing. Spatial indexing is used by databases to improve search speeds, of the three types of indexes namely B-Tree, R-Tree and GiST, the latter two are found to be useful for GIS data. Figure 10 displays the 3D R-tree index structure.

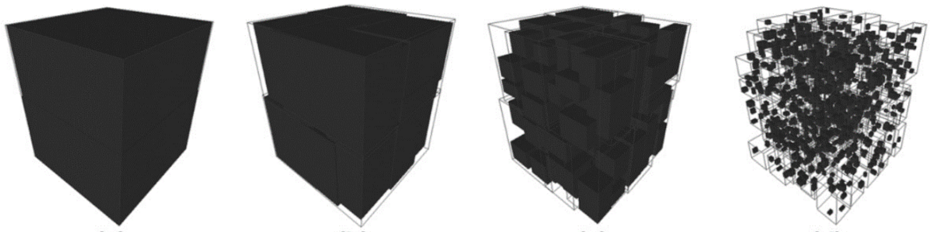

Figure 10. 3D R-Tree generation procedure. (a) Root layer. (b) 2nd middle layer. (c) 3rd middle layer. (d) Leaf layer [25].

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 utilized 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 neighborhood 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 Janečka et al. (2018) 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 were observed in the SDBMS domain where more spatial data types, functions and indexing mechanisms were supported. Two available SDBMS, Oracle Spatial and PostGIS were analyzed in detail, while other SDBMS such as Microsoft SQL Server, MySQL have been seen to follow Simple Feature Access international standard. Most of these software including ESRI support 2D topology very well, however 3D topology is not supported natively yet. Comparison of various SDBMS for storing, and representing large point clouds was done with various software excelling in some aspects. ESRI's TIN structure, Oracle Spatial providing suitable data structure and mechanisms, MonetDB's in-memory perspective rather than a buffer perspective and ability to move data between storage hierarchies, Oracle Exadata's flat table model for data loading and querying and handling large number of points are some of the features of the current SBDMs. A discussion on recent development of spatial databases follows with discussion on nD-array DBMS, comparison between file-based solutions vs. nD-array DBMS, and the development of modern Graphics Processing Units (GPUs) and their use in massive parallel architectures for processing large-scale geospatial data. In conclusion, the paper proposes a 3D topology model based on TEN synchronized with LADM specifications and the development of conceptual and physical model seems to be suitable for 3D cadastre and 3D registration. This topological model would utilize 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 [26].

6. CONCLUSIONS

In the last 20 years the researchers and professionals have paid the big attention to the 3D cadastre. Nowadays one can find the countries with legislation supporting the registration of 3D spatial units (Sweden, Queensland, Victoria, also the Netherlands, big cities in China like Shanghai). The registration of 3D spatial units can be seen as the first step towards the 3D cadastre. However, also the organizational and technical aspect have to be addressed. Even some countries do support the registration of 3D spatial units, this is done mostly using 3D drawings (e.g. survey sketch capturing the 3D geometry of the object or 3D pdf file showing the legal extent of 3D spatial units [27]). To enable the effective functioning of the 3D cadastre, the 3D data have to become an integral part of the cadastral spatial database. To meet this condition, the necessary steps are standardization in the field of 3D cadastre (ISO 19152 LADM), 3D information modelling (e.g. 3D LADM based country profiles) and further development of 3D spatial databases.

Another important technical aspect of the 3D cadastre is relation with other initiatives like BIM (Building Information Modelling). The capturing of 3D data is often seen as the most expensive phase of establishing the 3D cadastre. Re-usage of data like BIM could help to bridge this stage. The usage of BIM for the 3D cadastre purposes has already been addressed [28-30].

Even the developed LADM based profiles often have not yet been implemented in the production environments [31], the situation might be different in the future. For example, in the Czech Republic, the Strategy for the BIM implementation was approved by the Czech government. From 2026 the Czech Office for Surveying, Mapping and Cadastre is obliged to ensure the reusing of the BIM data for 3D cadastre purposes. It can be expected that this Strategy will enforce the change in the existing cadastral data model towards the registration of 3D spatial units. The cadastral data model could be then modified and extended to support the registration of 3D spatial units in the standardized way, according to the LADM possibilities and realized using well-functioning 3D spatial databases.

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