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Research and development in 3D cadastres

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ABSTRACT

Ten years after the first special issue of Computers, Environment and Urban Systems (CEUS) on 3D cadastres, seeing the progress in this second special issue is impressive. The domain of 3D cadastres has clearly matured in both research and practice. The ever-increasing complexity of infrastructures and densely developed areas requires proper registration of their legal status (private and public), which the existing 2D cadastral registrations can only partly do. During the past decade, various R&D activities have provided better 3D support for the registration of ownership and other rights, restrictions and responsibilities (RRRs). Despite this progress, of which an overview is given in this introduction paper (and is further elaborated upon in subsequent papers of this special issue), our research agenda for the next decade involves many challenges. This paper sketches six remaining 3D cadastres research topics: (1) shared concepts and terminology (standardization), (2) full life cycle in 3D (not only the rights), (3) legal framework, (4) creation and submission of initial 3D spatial units, (5) 3D cadastral visualization, and (6) more formal semantics.

1. Introduction

The increasing complexity of urban (and rural) spaces and their ever-increasing dense and intensive use require proper registration of their legal status (private and public). This registration cannot be provided in all situations by existing 2D cadastral registrations. The importance of 3D cadastres is illustrated by Singapore Land Authority's (SLA) new vision statement containing an explicit 3D component: "Limited Land – Unlimited Space." After past research and prototype developments, the present era is one in which the first 3D cadastral systems are in operation. Of course, this new era brings new experiences and challenges, such as registering volumetric parcels in both public registers and a 3D cadastral map, using non two-manifold geometries, designing 3D user interfaces tailored to 3D cadastre visualization and exploration, identifying specific types of situations that are best represented by 3D cadastre solutions (e.g., complex buildings, above and subsurface infrastructures, natural resources and related rights). These experiences and new challenges should be exchanged, investigated, and further improved to encompass legal, institutional, and technical factors.

It is important to realize that a 3D cadastre solution always depends on the local situation and is driven by user needs, land market requirements, the legal framework, and technical possibilities. Within the International Federation of Surveyors (FIG) 3D cadastres' working group (see Section 2), the concept of 3D cadastres with 3D parcels is applied in the broadest possible sense to comprise all country-specific meanings of 3D cadastres. Consequently, 3D parcels include land and water spaces both above and below the surface. However, every country has to decide on the types of 3D cadastral objects that need to be registered. Are these types related to real-world objects (buildings, utilities, or other constructions) or not (airspace of arbitrary subsurface parts)? If related to real-world objects, how can the relationship between the 3D cadastral registration (legal spaces) and the registration of real-world objects be maintained within the context of the geo-information infrastructure (GII)?

During the past decade, various 3D cadastre activities have been conducted. The commencement of the international awareness of this topic was marked by the first workshop on 3D cadastres, organized by Delft University of Technology in November 2001. After the 2001 workshop, the first special issue was created based on selected papers from the workshop, Computers, Environment and Urban Systems, Volume 27, Number 4, July 2003 (Lemmen & van Oosterom, 2003), which was subsequently followed by one or more sessions at every FIG working week and congress.

The remainder of this paper is organized as follows. Section 2 describes the FIG 3D cadastres working group, including its objectives, scope, and the workshops, resulting in this special issue. The six identified key research challenges in the area of 3D cadastres are presented in Section 3. Finally, Section 4 introduces the papers accepted in this special issue.

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2. The FIG 3D cadastres working group

The FIG Congress in April 2010 in Sydney decided to re-establish the working group on 3D cadastres (using the same logo as the earlier working group of 2002–2006; see Fig. 1) to exchange experiences and make further progress. The working group fit within the work plans of FIG commissions 3 ''Spatial Information Management'' and 7 ''Cadastre and Land Management.'' The working group investigates registration of the legal status of complex 3D situations. The starting point of the 3D cadastres working group of 2010–2014 was the observation that increasing information is required on rights, use, and value in complex spatial configurations (3D), whereas current cadastres do not offer sufficient information in such situations.

2.1. Objectives of the working group

The main objective of the working group is to establish an operational framework for 3D cadastres, including the following:

1. A common understanding of the terms and issues involved in 3D cadastres. After initial misunderstandings resulting from a lack of shared concepts and terminology in the early days, the concepts should now be further refined and agreed on based on the ISO 19152:2012 Land Administration Domain Model (LADM) that provides support for 3D representations.
2. Descriptions of the issues that should be considered (and to what level) before whatever form of 3D cadastres are implemented. One can think of a checklist for the implementation of 3D cadastres that will provide ''best practices'' for the legal, institutional, and technical factors. These findings will be translated into basic guidelines for the implementation of 3D cadastres.

In 2010, the state-of-the-art for 3D cadastres was obtained through the FIG questionnaire completed by many countries (http://www.gdmc.nl/3DCadastres/participants and click on the individual country/state to see the completed questionnaire). The questionnaire showed that there is no single best solution for a 3D cadastre. In all cases, for the establishment of such a cadastre, legal, institutional, and technical issues must be addressed. Ultimately, the level of sophistication of each 3D cadastre will be based on user needs, land market requirements, the legal framework, and technical possibilities. Therefore, in line with the ISO 19152 Land Administration Domain Model (LADM), the optimal 3D cadastre will be a trade-off between 2D and 3D cadastral solutions. Thus, addressing the issues that arise in the transition zones between 2D and 3D representations is also imperative.

The concept of 3D cadastres with 3D parcels has a wide variety of implementations. As stated in the introduction, 3D parcels include land and water spaces both above and below the surface. However, what exactly a 3D parcel is (or could be) depends on the legal and organizational context in the specific country (state, province). For example, in one country, a 3D parcel related to an apartment unit may be associated with an ownership right, whereas in another country, the government may be the owner of the entire apartment complex and the same apartment unit is related to a use right. Both cases relate to an explicit 3D parcel but with different rights attached. A third country may decide not to represent apartment units with explicit 3D geometries (and the 3D component is then ''just'' conceptual).

To accommodate the broad sense of a 3D parcel, a more formal definition is as follows. A 3D parcel is defined as the 3D spatial unit against which (one or more) unique and homogeneous rights (e.g., ownership or land use), responsibilities, or restrictions (RRRs) are associated with the entire entity, as included in a land administration system. Homogeneous means that the same combination of rights equally applies within the entire 3D spatial unit. Unique means that the spatial unit is the largest for which this is true. Making the unit any larger would result in the combination of rights not being homogenous. Making the unit smaller would result in at least two neighboring 3D parcels with the same combinations of rights.

2.2. Scoping

Several 3D cadastre options exist that should be investigated in greater detail, and the result will define the scope of a future 3D cadastre in a specific country.

1. What are the types of 3D cadastral objects that need to be registered? Are these objects always related to (future) constructions (e.g., buildings, pipelines, tunnels), as in Norway and Sweden, or could they be any part of the 3D space, be it airspace or subsurface space (both land or water columns), as in Queensland, Australia?
2. Should (subsurface) infrastructure objects, such as long tunnels (for roads, subways, trains), pipelines, and cables, be divided based on surface parcels (as in Queensland, Australia) or treated as one 3D cadastral object (as in Sweden)? For a subdivision, note that rights (and parties) should be associated with all parts, which is error prone in maintenance.
3. For the representation (and initial registration) of a 3D cadastral object, is the legal space specified by its own coordinates in a shared reference system (as is the practice for 2D in most countries) or is it specified by referencing existing topographic objects/boundaries (as in the ''British'' style of a cadastre)?

Note that there can be a difference between the 3D ownership space and the 3D restriction space; e.g., one can be the owner up to ±100 m around the earth's surface but may be allowed to build only from −10 to +40 m. Both ownership and restriction spaces result in 3D parcels, that is, 3D spatial units with RRRs attached. The ownership spaces (parcels) should not overlap with other ownership parcels, but they are allowed to overlap with other spaces; e.g., restriction parcels.

The list of topics addressed within the 3D cadastres working group is as follows: analysis of 3D use cases; 3D legal objects and physical objects; building units (apartments) as 3D parcels; 3D constructions as 3D parcels; utility networks as 3D parcels; airspace or subsurface space 3D parcels; potentially unbounded 3D parcels (toward the sky); natural resources (groundwater, mining) as 3D parcels; polluted areas as 3D parcels; spatial (zoning) plans as 3D parcels; institutional aspects; policy development related to 3D cadastres; the legal framework for 3D cadastres; range of RRR (rights, restrictions, and responsibilities) attached to 3D parcels; 3D data acquisition (survey plans); initial registration of 3D parcels; 3D data management; 3D validation of geometry (and topology); 3D cadastres and models; the relationship between 2D and 3D parcels; height representation (absolute/relative, 3D geometry and topology); 3D cadastres and time; implementation in a

Fig. 1. Logo of the FIG 3D cadastres working group.

cadastral database; visualization, distribution, and delivery of 3D parcels; 3D exchange formats; Web-based access to 3D parcels; 3D cadastres and the spatial information infrastructure (SII); 3D cadastres and usability; 3D planning of urban space; and prediction and monitoring of 3D land use, among other topics.

2.3. The second and third workshops

The second International Workshop on 3D Cadastre was organized in 2011 (Delft, The Netherlands) as a joint activity of the FIG, the European Spatial Data Research Organization (EuroSDR) and Delft University of Technology. The fact that the third workshop was not one decade, but just 1 year, later (2012, Shenzhen, China) was a clear indication of the maturation of the field. The third workshop was organized as a joint activity of Shenzhen Municipality, Wuhan University and the FIG. One main trend is the gradual move from research and prototypes toward the implementation and use of operational systems (backed by appropriate legislation).

The call for contributions to the second workshop resulted in 38 abstract submissions covering most of the previously mentioned topics. Based on their (very) good review scores, 32 contributions were selected. The authors of these abstracts submitted full papers to the workshop, which are included in the proceedings (van Oosterom, Fendel, Stoter, & Streilein, 2011). The call for contributions for the third workshop resulted in 27 abstract submissions, which is a large number considering that the 3D cadastre is quite specific and that the second workshop was organized less than a year ago. Again, the reviewers provided significant constructive feedback to the authors and were, in general, quite satisfied with the quality of the abstracts. A selection was made based on the review scores. Finally, for 21 contributions, the corresponding authors each submitted a full paper, which are included in the proceedings (van Oosterom, Guo, Li, Ying, & Angsüsser, 2012). The proceedings of the first (van Oosterom et al., 2001), second, and third 3D cadastres workshops are available in hard copy and online through the FIG 3D cadastres working group Web site (http://www.gdmc.nl/3DCadastres); see Fig. 2.

China, the host country of the third workshop, was well represented by a relatively large number of participants from cities with close to or more than 10 million inhabitants. The significant Chinese participation illustrates the rapid 3D developments and the urgent need for 3D cadastres in many of these large Chinese cities, of which Shenzhen is a prime example. During the workshop, a demonstration of the operational cadastral system showed current 3D cadastre practices in Shenzhen. The technical tour included a visit to multi-jurisdiction (Hong Kong–mainland China) 3D cadastral objects (a bridge and an immigration terminal) and to a sub-surface shopping complex in Shenzhen, which was registered using 3D parcels.

2.4. Invitations for the special issue

After the second workshop and in parallel with the (preparation of) the third workshop, the guest editor invited a limited number of authors to contribute to the special issue of CEUS. The invitations were based on reviews of the workshop contributions and the extent of the 3D cadastral topics to be covered. The journal articles needed to be significantly different from the workshop papers by including new material based on discussions at the workshop and other new developments. All submitted papers were reviewed by three reviewers selected by the guest editor and were approved by the editor-in-chief. No reviewer was also an author of a paper submitted for inclusion in the special issue. Section 4 provides an overview of the papers accepted for the special issue.

3. Key research challenges

During the past few years, numerous developments have occurred with respect to 3D cadastres. As indicated in the previous section, one important development is gradually moving from research and prototypes toward the implementation and use of operational systems (backed by appropriate legislation). This development brings additional experience and forms the basis for new requirements and new research challenges. During the second and third 3D cadastre workshops, a number of key topics for future 3D cadastre research were raised, including: (1) shared concepts and terminology (standardization), (2) full life cycle in 3D (not only the rights), (3) legal framework, (4) creation and submission of initial 3D spatial units, (5) 3D cadastral visualization, and 6. more formal semantics.

3.1. Shared concepts and terminology

Despite the fact that we now have had three 3D cadastre workshops, many sessions at FIG working weeks and congresses, and several journal publications, confusion still exists over terminology and key concepts. Terms such as 3D SDI and ubiquitous cadastre essentially refer to the same overarching concept of an information infrastructure that includes both 3D legal space and 3D representations of physical real-world objects (e.g., CityGML-like). Meaningful communication is enabled by using existing standards where available, such as the LADM (ISO, 2012), and by further discussing terminology and concepts during international events, such as, for example, the 3D cadastres workshop series, the FIG working weeks, and the FIG Congress.

Fig. 2. Select 3D cadastre scenes in Delft and Shenzhen (from the covers of the 2011 and 2012 FIG 3D cadastres workshop proceedings, respectively).

3.2. Full life cycle in 3D

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

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

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

3.3. Legal framework

Arguably, more *international comparative* legal research should be conducted (Paulsson, 2012), although doing so may be very difficult because of differences in national legislation and terminology. The current informative Annexes F "Legal Profiles" and J "Code Lists" of the ISO 19152, LADM and the Legal Cadastral Domain Model (LCDM) as developed by Paasch (2012) in the context of his recently completed PhD thesis at KTH Stockholm in Sweden, may be used as starting or reference points in international legal research and development. For example by adding more content and "structure" to the code lists in the current LADM Administrative Package.

3.4. Creation and submission of initial 3D spatial units

In many countries, actual surveying work is conducted outside the cadastral organization; thus, it is important to clearly define what are acceptable (valid) 3D cadastral object representations and how these should be formatted before submission. Challenging issues include the fact that the involved geometries may be: (1) non-two-manifold (self-touching in edge or node; see Fig. 3), (2) partially open (up into the sky or down into the earth), and/or (3) consisting of non-linear (curved) primitives in some legislations. It is also important to define the formal validity of mixed 2D and 3D cadastral parcels (Thompson & van Oosterom, 2012). These aspects are not well supported by current GIS, CAD, and DBMS software and generic ISO standards such as ISO 19107 (spatial schema).

3.4.1. 3D cadastral visualization

The visualization and/or interaction with 3D cadastral parcels requires more attention and may be quite different from the more well-known visualization of 3D city models (Wang, Pouliot, & Hubert, 2012). Some specific key points are as follows: (1) how to visualize dense 3D volumetric partitions such as in a complex building because the first visible outside layer of 3D spatial units blocks a view of the others—solutions could be based on selections and the use wireframes and semi-transparent objects, showing cross-sections/slices, or applying slide-out layer techniques as developed in the Russian prototype; see Fig. 4, (2) how to display open or unbounded parcels, (3) how to include the earth's surface and/or other reference objects (e.g., CityGML-like) for 3D cadastral parcels, (4) how to provide the proper depth cues for subsurface legal spaces related to utilities (e.g., use stereo, perspective, movement/rotation, or connecting vertical sticks from a subsurface object to the earth's surface).

3.5. Formal semantics

Finally, more formal semantics are requested within the 3D cadastre domain. For example, an ontology should be further developed in OWL (or RDF) for 3D land administration based on the foundation of ISO 19152, not only for a 3D cadastre in the narrow sense, but in the sense of the entire chain of activities of 3D (rural or urban) development; see Section 3.2. Further formalization of the involved information will better support the various steps and enable as much automation as possible based on formal knowledge and reasoning (Soon, 2012).

4. Overview of accepted papers

This special issue contains seven other papers that will be introduced and contextualized shortly. The paper topics comprise the entire spectrum of the 3D cadastral research agenda: legal framework, vertical reference, cost-benefit analysis, digital lodgment and validation, operational 3D cadastral systems (examples from China and The Netherlands), and, finally, comparing (3D) cadastral information models using the LADM.

The legal foundation is crucial for (3D) cadastres because the spatial units are defined by rights, restrictions, and responsibilities. The first paper, by Jenny Paulsson and Jesper Paasch (KTH Stockholm, Sweden), "3D Property Research from a Legal Perspective," (Paulsson and Passch, 2013) analyses conference papers and other 3D cadastre publications written in English during the last decade to assess the distribution of interest areas and trends. More research was found to have been conducted on technical aspects and registration than on legal aspects, and there was a focus on national legislation within the legal category. Paulsson and Paasch state that more fundamental legal research and international comparative studies are required.

Contending with the third dimension may well be more complicated than one might initially expect, as explained in the paper by

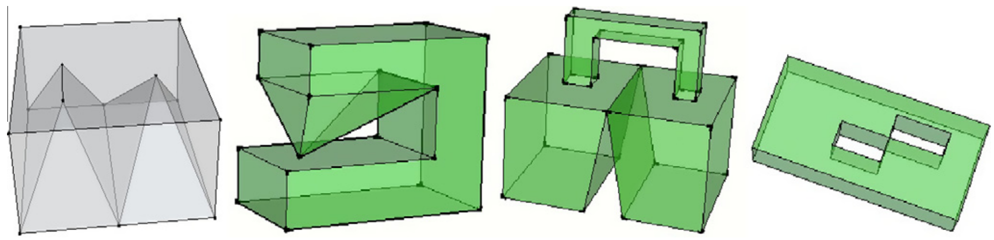

Fig. 3. Valid but non-manifold 3D parcels (illustration created by Shen Ying, Wuhan University).

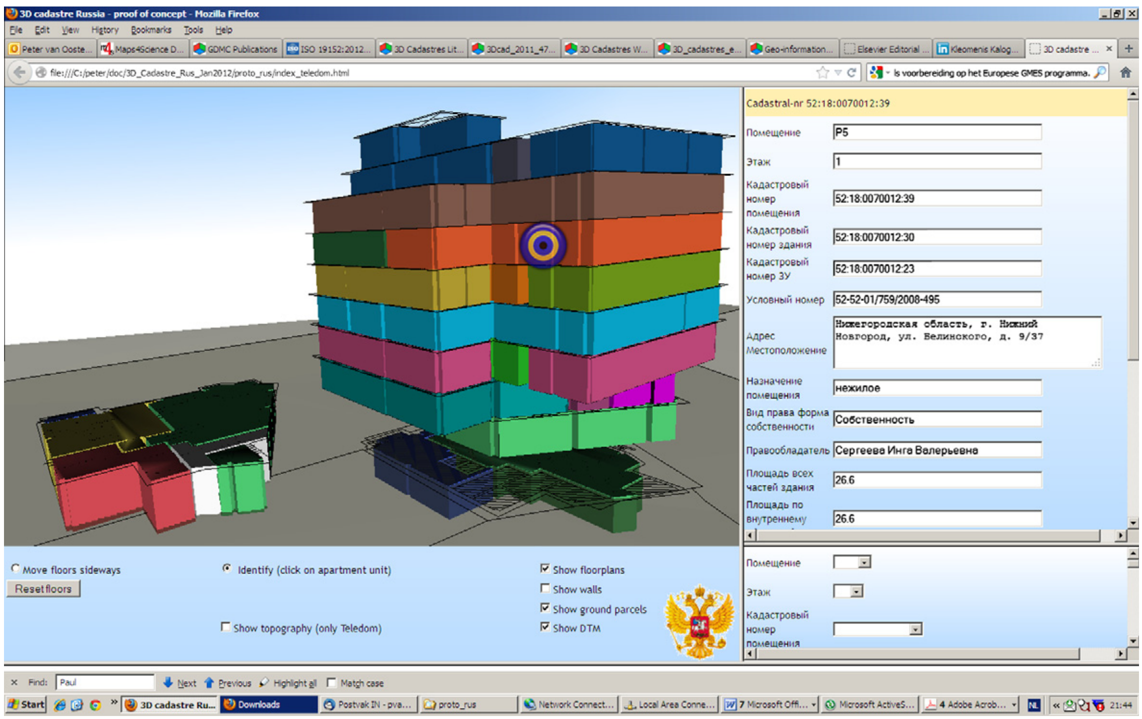

Fig. 4. Interacting with 3D parcels: slide-out of a layer with rights from a building as developed in a 3D cadastre prototype for the Russian Federation (Vandysheva et al., 2012): Floor_01 dragged outside the building.

Gerhard Navratil and Eva-Maria Unger (TU Wien, Austria), "Requirements of 3D Cadastres for Height Systems." (Navratil and Unger, 2013) The vertical reference is non-trivial because the earth is neither homogeneous nor flat, and the plumb lines are slightly curved and not parallel. The earth is also dynamic because of, for example, plate tectonics, erosion, and human intervention, thus further complicating matters for a stable vertical reference system that is needed because (3D) cadastral data should be reliable over a long time span, such as decades or even centuries. Arguably, no height reference system fits all needs, and different systems may be optimal for different (parts of) countries.

A sustainable 3D cadastre will exist only if a healthy balance exists between the costs and the benefits. One may wonder whether this "tool" is only suitable for developed (rich) countries or is equally suitable for developing and lower-income countries. This question is addressed by Charisse Griffith-Charles and Michael Sutherland (University of the West Indies, St. Augustine, Trinidad and Tobago) in "Analysing the Costs and Benefits of 3D Cadastres with Reference to Trinidad and Tobago." (Griffith-Charles and Sutherland, 2013) An assessment is conducted to determine where the existence of a 3D cadastre would improve the activities currently supported by a 2D cadastre. An assessment is made of the percentage of a country's area in which 3D rights exist and the benefits of using a 3D cadastre to manage those rights are quantified. This assessment is compared with the estimated increase in costs of the 3D cadastre. This paper finds that, in Trinidad and Tobago, a positive benefit/cost balance for using a 3D cadastre is largely isolated to urban, densely populated areas and oil mining areas.

The initial creation of the 3D geometric representation of volume parcels is the topic of a paper by Sudarshan Karki, Rodney James Thompson, and Kevin McDougall (Queensland Government, Australia), "Development of Validation Rules to Support Digital Lodgement of 3D Cadastral Plans." (Karki et al., 2013) The paper described what should be solved to automate the validation of 3D cadastral plans to accept registrations. A key issue is agreeing on and formalizing what should be considered as valid 3D cadastral parcel geometries. Although a set of validation rules is proposed, the nature of the problem makes this set incomplete and it remains as such. However, a "checklist" of issues to be addressed has been composed.

The demand for a 3D cadastre within a setting of fast economic growth and rapid urbanization is described by Renzhong Guo, Lin Li, Shen Ying, Ping Luo, Biao He, and Renrong Jiang (Shenzhen Municipality and Wuhan University, China) in "Developing a 3D cadastre for the Administration of Urban Land Use: A Case Study of Shenzhen, China." (Guo et al., 2013) The urbanization requires more efficient use of space above and below the surface parcels. This paper presents the design and development of a 3D cadastral

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system in Shenzhen that relies on current legislation, administration, and 3D technology. The 3D extension is embedded in the existing 2D cadastral system. The administration of 3D parcels can be realized without an alteration in the framework of current administrative procedures.

Jantien Stoter, Hendrik Ploeger, and Peter van Oosterom (Delft University of Technology, The Netherlands) describe in their paper "3D Cadastre in the Netherlands: Developments and International Applicability" (Stoter et al., 2013) the cadastral system extension for the registration of 3D rights and restrictions in The Netherlands that fits within the ISO 19152, LADM. The implementation will be conducted in two phases. The first phase of the solution does not require a change of legal frameworks and is based on adding 3D descriptions in 3D PDF format in the property transfer deed. 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. The first phase is now operational and based on the experience gained and problems solved or encountered. The second phase will be developed.

Finally, Jacynthe Pouliot, Marc Vasseur, and Abbas Boubehrezh (Laval University, Canada) propose in their paper, "How the ISO 19152 Land Administration Domain Model Performs in the Comparison of Cadastral Systems: A Case Study of Condominium/Co-ownership in Quebec (Canada) and Alsace Moselle (France)," (Pouliot et al., 2013) an original approach for comparing cadastral systems with a focus on vertical divided co-ownership. The modeling of Quebec (Canada) and Alsace Moselle (France) condominium units is expressed in LADM terms, enabling a comparative analysis with an emphasis on the third dimension. The formal description of a common set of concepts and terms such as defined by LADM enabled a visual comparison through which both systems can now be compared side by side, class by class, and attribute by attribute. The use of the LADM specification was not always evident and required significant data modeling skills.

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The key future research aspect of this paper is based on discussions that occurred during the two most recent FIG 3D cadastres workshops: Delft, 2011 and Shenzhen, 2012. The program committee members of the two workshops are acknowledged for their diligent work in assessing the quality of the submissions. Many thanks to the local organizing committees in The Netherlands and China, respectively, and especially to my fellow editors, Elfriede Fendel, Jantien Stoter, and André Streilein (2011) and Renzhong Guo, Lin Li, Shen Ying, and Stephan Angsuesser (2012), respectively, for the pleasant team-work. The reviewers of the (accepted and rejected) papers in this special issue are thanked for the constructive critical reviews and, in many cases, for their patience when reviewing the revised versions. Jantien Stoter is gratefully acknowledged for proofreading this introduction paper. Special thanks to Jean-Claude Thill for the constructive cooperation during the preparation of this special issue.

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