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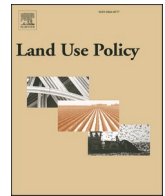
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Trends in 3D cadastre – A literature survey

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ABSTRACT

The formation and alteration of real property and rights, restrictions and responsibilities are important parts of land administration. Research on the distribution of publications in the three-dimensional (3D) cadastral domain has been in focus as a specialised part of real property research during the last decades. A number of literature surveys on research trends in the domain show a growing number of publications during the last decades. The number of publications have increased considerably within a range of topics, classified into legal, technical, registration and organisational categories of 3D property. The purpose of the research presented here is to contribute to these analyses of the number and thematic distribution of the 3D cadastral domain literature by analysing three aspects: 1) To add to the recent study by including 3D cadastre publications published during 2021 (Paasch and Paulsson, 2021a, 2021b); 2) To briefly analyse the classification of 3D cadastre research in technical programmes and proceedings of major conferences focussing, in total or in part, on 3D cadastre. 3) The results are used to contribute to the discussion regarding if the 3D cadastral domain is too diverse today to talk about a single 3D cadastral domain. An input to the discussion of what constitutes a domain is provided from an analysis of another land administration research topic that is often addressed in relation to 3D real property research; the international standard for land administration, the Land Administration Domain Model, LADM, ISO 19152.

1. Introduction

The formation and alteration of real property and rights, restrictions and responsibilities are important parts of land administration. Research on the distribution of publications in the three-dimensional (3D) cadastral domain has been in focus as a specialised part of real property research during the last decades. During the last decade, several literature surveys on trends and development in 3D property research have been published. The first study, to our knowledge, was an initial study on the occurrence of legal topics in publications by Paulsson and Paasch (2013), followed by an analysis and classification of 3D research topics by the same authors (Paulsson and Paasch, 2013), also from a legal perspective. The survey identified and analysed 159 publications within the domain covering 2001–2011. The number of publications have in other words increased considerably within a range of what we call major categories, such as *legal*, *technical*, *registration* and *organisational* aspects of 3D property. This article is based on and adds to the conference paper on new trends in 3D cadastre research by Paasch and Paulsson (2021b).

The term cadastral domain covers in this research a wide range of

land administration issues such as registration of ownership and other real property rights, fiscal rights and other elements influencing the use, exploitation and management of land, water and air. See Paasch (2012, p. viii)).

In previous studies, we have seen that there are some recurring themes and topics in the published research. We thought that it would be of interest to study these research topics more in detail to find out what is included in them, where the 3D cadastre research seems to be heading in these fields, and what could be interesting to study and develop further. We chose these topics among those identified in the Paasch and Paulsson (2021a) survey, which identified some 3D cadastre topics that have gained increased focus during the investigated period but were not analysed in detail in the study. They are, for example, marine and water applications, valuation, Building Information Models (BIM) and 4D cadastre. These research topics are investigated further in this paper. The included publications are part of the 2021 study but are analysed more in detail in this paper in relation to some of the topics. To further add to the trend overview, conference topics have also been identified and, as a result of where 3D cadastre research seems to be heading, a

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discussion of 3D cadastre as a domain and its contents is also added.

1.1. Aim

The aim of this article is to identify and describe some recent trends in 3D cadastre research, based on a literature survey of publications on 3D cadastre research from the years 2012–2021. The purpose is not to make a full identification and description of all current trends, nor to outline future trends in 3D cadastre research in detail, but to present an overview of the research area and discuss possible coming research trends. 3D cadastre research covers a multitude of sub-disciplines and has in Oosterom (2018) been divided into e.g., legal foundations, initial registration of 3D parcels and visualisation. Three-dimensional real property has become part of our daily lives and is registered in many nations' national cadastres. We noticed that different types of topics amongst the studied publications appeared with some regularity in the survey and we judged it to be of interest for the scientific community to present a preliminary analysis of them to describe some possible current trends in 3D cadastre research. Examples are used to provide reference to, in our view, key publications within the identified research areas. They are selected from the publications found in the mentioned literature survey, although there is much more ongoing research. The main categories are analysed in the same manner as in the 2012 and 2021 surveys, i.e. classifying them into legal, technical, registration and organisational categories.

The purpose is also to contribute to the above mentioned analyses of 3D cadastral domain literature by a: 1) To add to the [Paasch and Paulsson \(2021a, 2021b\)](#) studies by analysing the most recent 3D cadastre publications published during 2021; 2) To briefly study the classification of 3D cadastre research in technical programmes and proceedings of some major conferences focusing, in total or in part, on 3D cadastre. 3) To contribute to the discussion regarding if the 3D cadastral domain is too diverse today to talk about a single 3D cadastral domain. An input to the discussion of what constitutes a domain is provided from an analysis of another land administration research topic that is often addressed in relation to 3D real property research; the international standard for land administration, the Land Administration Domain Model, LADM, ISO 19152.

2. Method

This study is made by analysing the content of published research on 3D cadastre. The publications that were studied were identified through database searches, such as ScienceDirect, JSTOR and Scopus. The same keywords as in [Paasch and Paulsson \(2021a\)](#) were used: “3D cadastre”, “3D cadastral”, “3D cadaster”, “3D real property” and “property strata”, and combinations thereof. The study includes publications in peer-reviewed journals, conference papers as well as other types of scientific publication, e.g. book chapters. Many research publications in the field are published in the proceedings of 3D cadastre conferences/workshops, which is a reason for why these publications have been included. The same principle as in the previous Paulsson and Paasch surveys was used, i.e. to limit the study to English language publications which are more accessible to the international research community. This has limited the number of publications, e.g. excluding research on national 3D property issues published in the language of the country studied.

In order to classify the publications in the survey, the classification system that was developed in the previous literature surveys by [Paasch and Paulsson \(2013, 2021a\)](#) was used, for the purpose of being able to compare the results with the previous studies. This classification system was used for dividing the published research into different categories. A study of the thematic distribution of the publications was conducted and the publications were classified according to this classification system.

The theme of each publication was analysed and assigned to one of four categories. As in the previous surveys, primary and secondary

categories were used, since most publications could be assigned to more than one category where several themes are addressed in the same publication. What is called the ‘primary theme’ is the dominant theme in each publication and the ‘secondary theme’ is the less dominant theme (or themes) of the publication.

The four categories legal, technical, registration and organisational were used for classification, with the same contents of each category as in the previously mentioned studies (see [Paasch and Paulsson, 2021a](#)): “Legal: The legal category contains publications on topics such as real property rights, restrictions, responsibilities, real property, superficies solo credit, security of tenure, legislation, subdivision, spatial planning, legal objects and the legal framework.

Technical: The technical category contains publications on topics such as database management, spatial data infrastructure, data models, GIS, visualisation and geometrical representation, cadastral surveying, geometry, topology, exchange formats and the technical aspects of distribution and delivery.

Registration: The registration category contains publications on matters that concern the registration of 3D property in land administration systems, such as the content, storage, structure and maintenance of 3D property information. “Land administration system” refers to any system that stores 3D property information, such as land registers and purpose cadastres.

Organisational: The organisational category contains publications on institutional, management and capacity-building issues. Organisation is primarily a question of efficiency and how to organise and manage 3D property. Examples of organisational issues include good governance, operational aspects and financial aspects.”

An additional category, others, has also been added. The topic contains publications not directly associated with the other topics, such as general introductions and editorial texts.

The previous surveys showed some recurring 3D cadastre topics with a rather frequent existence, such as standardisation and 4D cadastre. In the previous surveys, these topics were identified, although not further analysed. The analysis was therefore extended to include these topics in the investigation with the purpose of studying these research topics more in detail in order to find out what is included in them and presenting more in detail some examples of such publications to show what they discuss. The trends of the studied period were identified and the distribution of research classified into some major topics is presented. No detailed statistical trend analysis was made since the quantity of collected data is too limited. However, the actual number of publications in each category is of less importance, since they only show the history of 3D cadastral research. It is rather the trend patterns that are of interest, to indicate where research may be heading in the future.

From the survey 2012–2020 and adding the 2021 data, visualisation, LADM and other standardisation were identified as major topics and thus further analysed regarding the distribution between the four categories legal, technical, registration and organisational. [Paulsson and Paasch \(2021b\)](#) identified areas that could be of interest for further research, namely BIM, 4D cadastre, marine and water applications and valuation. The contents of these topics were further analysed in this paper and examples were selected to show examples of research carried out on these topics.

The survey focuses on the research contents and trends, as opposed to the FIG (International Federation of Surveyors) 3D cadastre questionnaires that have been carried out in 2010, 2014, 2018 and 2022 with the purpose of making a world-wide inventory of the current status of 3D cadastre practice in a number of countries, as well as their plans and expectations for the near future. No direct comparison between these studies could thus be made, although this article includes a discussion on some topics occurring in the FIG questionnaires and their relation to the identified research trends in this study.

Technical programmes and proceedings from two major conference types in the field, the 3D cadastre workshop and the FIG Working Week, with the main theme or sessions on 3D cadastre, were studied and a

classification was made of the themes.

3. Previous research

3.1. Literature review 2001–2011

Paulsson and Paasch (2013) made a literature review of publications on 3D cadastre research to analyse the distribution of interest areas and the occurrence of legal aspects and trends within this field during the years 2001–2011. A total of 156 publications were analysed from those years and a classification was made of the surveyed publications into the main groups; *legal (L)*, *technical (T)*, *registration (R)* and *organisational (O)*. Out of the 156 publications, 28 publications were assigned to the legal category, 63 to the technical category, 59 to the registration category and six to the organisational category. Many of the publications could be assigned to more than one of these main categories.

The focus of the study was from the legal perspective. Taking a closer look at the publications in the legal category, most studies addressed national legislation and the practical use of (national) legislation. Other identified trends related to practical application of 3D property concepts, registration of 3D property, modelling of 3D property and standardisation of 3D property.

3.2. Literature review 2012–2020

Paasch and Paulsson (2021a, 2021b) conducted a follow-up study of the eight years that had passed since the 2013 survey covering 2001–2011. They identified, analysed and discussed the content of 530 publications from 2012 to 2020. The study showed that 3D cadastre publications mainly have focused on technical and registration issues, even if there is an increase in research concerning legal and organisational topics compared with the 2013 survey.

The literature surveys made a classification of the surveyed publications into the main groups; *legal*, *technical*, *registration* and *organisational*. Of the total of 530 publications identified during the analysed years, 77 publications were assigned to the legal category, 254 to the technical category, 165 to the registration category and 25 to the organisational category. The survey also showed that many of the publications could be assigned to more than one of the main categories. The study also investigated the occurrence of some sub-themes such as visualisation and standardisation. Furthermore, the results were compared with the previous study by Paulsson and Paasch (2013) of the years 2001–2011.

3.3. Other literature surveys

A number of other literature surveys on research trends in the domain show a growing number of publications during the period. Such literature studies on 3D cadastre research are Döner (2021) and Tekavec et al. (2018).

The studies by Tekavec et al. (2018) and Döner (2021) can only in part be compared with the Paulsson and Paasch (2013) and Paasch and Paulsson (2021a) (2021b) studies due to the fact that they are not executed in the same way and covering the exact same time periods. Döner (2021) uses a classification into *legal*, *registration* and *technical* topics, whereas Paulsson and Paasch use *legal*, *registration*, *technical* and *organisational* as main topics for their classification, which makes a comparison difficult. Furthermore, for example, the study by Döner (2021) is limited to analysing 283 publications, whereas the Paulsson and Paasch study identified 475 publications during the same period, 2012–2019. The study by Tekavec et al. (2018) focussed on internationally recognised studies 2000–2010 and 2011–2017 on 3D cadastre after 2010. The study is of interest but did not produce any quantitative data allowing comparison with this study. Another review of interest for this study is an LADM literature review covering 2012–2020 (Polat et al., 2021), presenting a bibliometric analysis from 2012 to 2020. The

paper analysed 175 LADM related scientific publications, classifying them into the same categories as in Paulsson and Paasch (2013): *Legal*, *technical*, *registration* and *organisational*. It is of interest to note that the contribution is similar to the 3D cadastre publications with the majority of publications in the technical and registration categories followed by the legal and organisational categories, in descending order.

4. Results

Looking at the distribution of topics by re-examining the 2012–2020 data and adding 2021 data, an increase in publications of other topics within the main topics has been identified throughout the investigated period on the topics. Visualisation, LADM and LADM related standardisation topics have been identified as other research topics in Paasch and Paulsson (2021a). Other topics were identified as interesting for the scientific community in Paasch and Paulsson (2021b); Building Information Modelling (BIM), 4D cadastre, Marine and water applications and valuation. They have however not been investigated in detail yet. The contents of the selected areas are presented more in detail below. They are numerically not significant, but may still give an indication on where 3D cadastre research is heading in the future.

The main categories are described in Section 4.1, the visualisation, LADM and non LADM standardisation topics are analysed in the categories in Section 4.2, and the Building Information Modelling (BIM), Marine and water applications, valuation and 4D cadastre are described and exemplified in Section 4.3.

4.1. Distribution of main categories 2001–2021

In total for the year 2021, 75 publications were found. Out of these 75 publications, 12 were assigned to the legal category, 37 to the technical category, 23 to the registration category and 2 to the organisational category. There was also one general publication that was in the form of an overview and therefore not possible to assign to a specific category. Thus, the least researched category was the organisational category, but with a comparatively low number belonging to the legal category as well. The technical category was found to be the largest, with as many publications as all the other categories together.

Studying more carefully the publications from 2021, it can be noticed that there have been more publications during this year compared to the two previous years. A reason for this is the 3D cadastre conference that took place in 2021. During the period 2012–2021, the only year with a number of publications exceeding 2021 is 2018 when the previous 3D cadastre conference was held. The distribution of the legal, technical, registration and organisational categories was similar to recent years. From the survey it could also be noticed that most publications could be assigned to more than one category, i.e. one primary category and one secondary category. In the secondary category, there were 13 publications in the legal category, 18 in the technical category, 14 in the registration category and 5 in the organisational category, thus a more even distribution between the categories than in the primary category. (Fig. 1).

The publication types from 2021 are peer review journal articles and conference proceeding papers, where 39 were journal articles and 36 were conference papers. The distribution is shown in Fig. 3 below together with the results presented in Fig. 2 and 3.

4.2. Visualisation, LADM and other standardisation

4.2.1. Visualisation

The visualisation topic was found in total in 85 publications. The majority was classified as belonging to the technical (44) and registration (26) categories. A total of 13 publications were identified as belonging to the legal category and only 2 publications to the organisational category. The technical and registration aspects have been in focus in the first part of the investigated period, but the legal aspect has

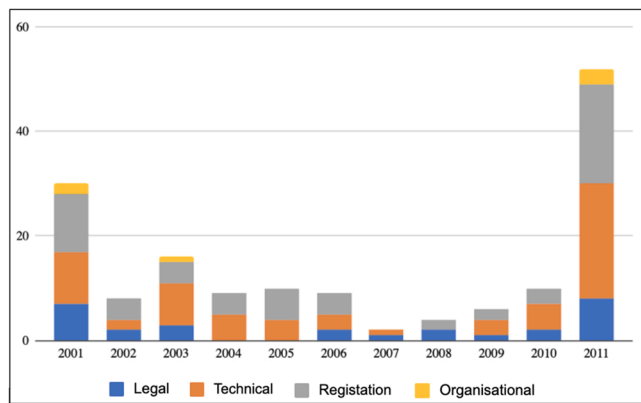


Fig. 1. Distribution in numbers of publications in the main categories 2001–2011 (Based on Paulsson and Paasch, 2013).

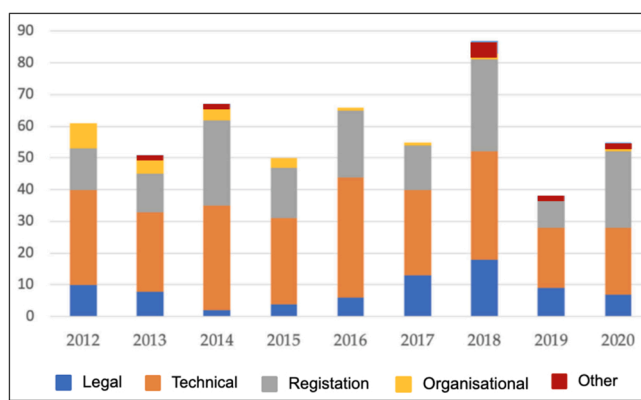


Fig. 2. Distribution in numbers of publications in the main categories 2012–2020 (Based on Paasch and Paulsson, 2021a).

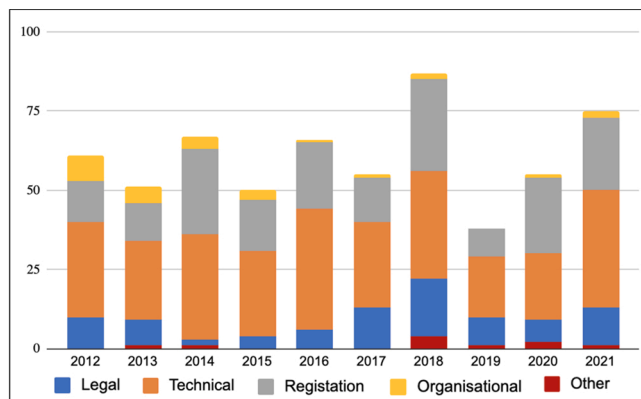


Fig. 3. Distribution in numbers of publications in main categories 2012–2021.

appeared in publications in the later part of the period. However, organisational aspects are only sparsely represented. The number of publications has increased annually, but with a drop in 2019. See Fig. 4.

4.2.2. LADM

The LADM topic was found in total in 81 publications. The majority was classified as belonging to the registration (58) and technical (31) categories. A total of 21 publications were identified as belonging to the legal category and only 1 publication to the organisational category. There has been an increase in publications during 2021 in all categories, especially registration, except in the organisational category.

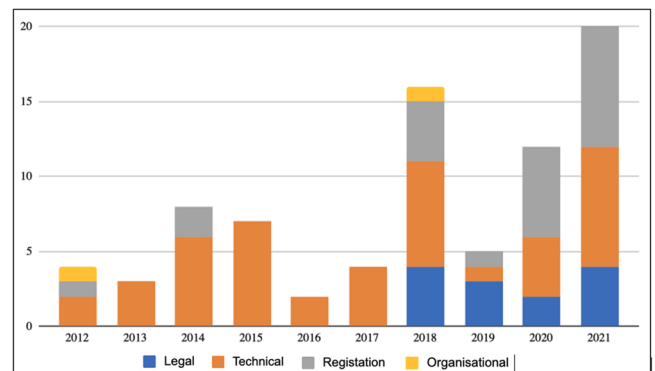


Fig. 4. Distribution of the visualisation topic in numbers in the main categories 2012–2021.

According to Polat (2019), standardisation studies on land-based issues (for example cadastre, planning and real estate valuation) have significantly changed the traditional view on land administration, encouraging LADM related research from different perspectives. In other words, the LADM domain has expanded from being a quite limited undertaking describing the core elements of land administration, such as rights, restrictions and responsibilities (RRR), into a much broader domain with a multitude of research topics, such as mass valuation (e.g. Šiško et al., 2022), conceptual data model for 3D underground land administration (e.g. Saeidian et al., 2022) and data models for implementation of an LADM based 3D digital cadastre (Atazadeh et al., 2022). The same seems to be happening with the 3D cadastral domain, encompassing more research areas in recent years, as described above.

The challenge of classifying publications to a specific category has also been noticed by Polat et al. (2022) presenting a bibliometric analysis of LADM research 2012–2020. They used the same main categories, i.e. legal, technical, registration and organisational, as in Paulsson and Paasch (2013). The problem of classification is also mentioned in Polat et al. (2022), indicating in our view that the LADM area also has developed into a (too) large research area in general. (Figs 5 and 6).

4.2.3. Other standardisation

With “other standardisation” are publications on non-LADM related standardisation topics, such as the INTERLIS, LandInfra and CityGML standards. The topic was found in 36 publications. The majority of publications were classified as belonging to the legal (44) and technical (14) categories. No publications were identified as belonging to the registration or the organisational categories. The number of publications peaked in 2021 with publications describing legal and technical issues.

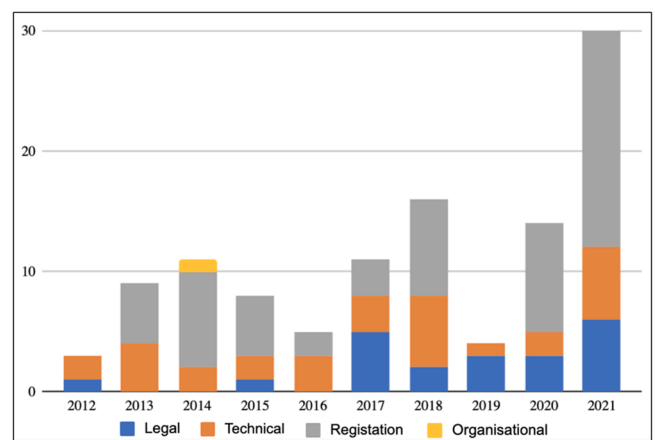


Fig. 5. Distribution of the number of publications of the LADM topic in the main categories 2012–2021.

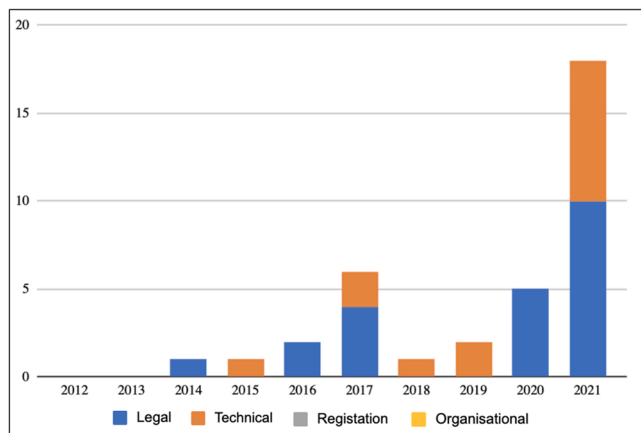


Fig. 6. Distribution in number of publications of the other standardisation topic in the main categories 2012–2021.

4.3. BIM, 4D cadastre, Marine and water applications, valuation

Out of the 530 publications analysed in the Paasch and Paulsson (2021a) study, 22 publications were identified as BIM related, 11 as 4D cadastre related, 11 related to marine and water applications, while 8 publications dealt with valuation topics.

4.3.1. BIM

22 publications were identified as belonging to the BIM theme. Focus in the publications is also on modelling, such as the comparison of three types of BIM-based models for managing 3D ownership interests (Atazadeh et al., 2016), and extending a BIM-based data model to support 3D digital management of complex ownership spaces (Atazadeh et al., 2019). Other topics are the use of open BIM standards to source legal spaces for a 3D cadastre (Oldfield et al., 2017), how BIM can be used to visualise 3D property (Andrée et al., 2018), and using 3D BIM modelling for value-based land share calculations (Simsek, 2017). Further examples are BIM-enabled spatial queries for retrieving property boundaries (Barzegar et al., 2020) and the feasibility to use a BIM-driven approach to support building subdivision workflows (Olfat et al., 2019), providing a mechanism for stakeholders to document, visualise, analyse, share and reuse 3D digital cadastral data. See Fig. 7.

4.3.2. 4D Cadastre

The 11 publications identified in the study that belong to this category describe different aspects of 4D cadastre. The identified publications are rather evenly distributed through the investigated period with one publication per year during the first 7 years, except in 2016 where

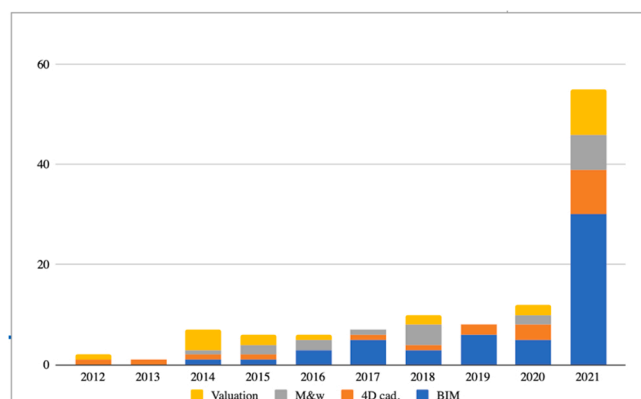


Fig. 7. Distribution of publications in numbers with BIM 4D, cadastre, marine and water (M&w) and valuation topics 2012–2021.

we did not identify any publication focusing on 4D cadastre. The years 2019 and 2020 showed a small increase in publications to 2 and 3 annually. It would make no sense to analyse these few publications statistically, but they may be indicative of coming research interests concerning 4D cadastre. Examples are data and implementation issues from conventional systems to multipurpose 3D and 4D cadastral systems (Paixao et al., 2012). Considering the categories presented in Paasch and Paulsson (2021a), the majority (6) of the 4D cadastre publications belong to the registration class, while four of them can be classified as technical and one publication in the organisational category. We did not identify any 4D cadastre publications belonging to the legal class.

The 4D cadastre topic focuses on the development of the concept of 3D cadastre by adding a time element. 4D cadastre is, in principle, identical to 3D cadastre but with a time component added. The 11 publications originate from a number of countries active within this research topic, such as Australia, the Netherlands, Turkey, Hungary, China, Indonesia, Argentina, Croatia and Indonesia. One example is Suhari et al. (2020) describing the implementation of the concept of 4D cadastre for land disputes and natural disasters, such as earthquakes, where time is a vital factor for managing these man-made or natural changes in the nation's land administration system(s). Another example is Thompson et al. (2019), who discuss the implementation of a data schema for 4D/5D cadastre. They believe that there is a need for time-related information in the cadastre, such as being able to track patterns of subdivision and land use through the past. See Fig. 7.

A topic within the 4D cadastre area is national studies on implementations of 4D cadastre, such as in Croatia (Vucic et al., 2014), Germany (Seifert et al., 2015) and the conformity of LADM for modelling 3D/4D Cadastre situations in Turkey (Döner and Biyik, 2013). Other topics are LADM related, such as the implementation of an LADM versioned object class for representing spatio-temporal 4D objects (Sulistyawati et al., 2018).

Constructing topological models for three-dimensional and dynamic cadastral management systems based on generalised maps are also focused upon in the studied research, see e.g. Ding and Shao (2020).

4.3.3. Marine and water applications

The marine and water applications topic is mainly focusing on the different issues that affect the construction of a 3D LADM compliant marine and water cadastre, such as legal and technical aspects, as well as developing an institutional framework and administration system. Out of the 11 publications that were identified in this topic, they were distributed rather evenly between the years in the studied period. A few countries are active in this research topic, from countries such as Trinidad and Tobago, Greece, Argentina, Malaysia, Ukraine and Poland. Considering the distribution presented in Paasch and Paulsson (2021b), the majority (7) of the marine publications belong to the registration class, while two of them can be classified as organisational and one publication each in the legal and technical categories.

The publications present research on different aspects of marine and water applications. For example, the concept of using water cadastre as a subsystem of the 3D cadastre by investigating the contents of water cadastre databases in Poland and possibilities of using them in building the 3D cadastre is also discussed in Mika et al. (2018), presenting a Real Estate Cadastre model based on synchronisation of the Land Register databases with the water cadastre databases. Hisham et al. (2015) present the Malaysia perspective on sustainable marine space management and propose a method of implanting marine space governance. Dubnytska and Krelshteyn (2018) discuss 3D cadastre as a tool for water bodies account, analysing the problems of cadastral systems in Ukraine and providing examples of water objects representation in a three-dimensional geoinformation environment. Alberdi and Erba (2018); Alberdi and Erba (2020) address modelling of legal land objects for water bodies in the context of 4D cadastre, i.e. considering the time aspect. They describe rivers as legal land objects in the 4D cadastre and evaluate the need to implement multidimensional registers with the

example of the Argentine cadastre.

A related question is how the international standards and practices of the land administration domain can be used for managing the marine environment. Sutherland et al. (2016) study the development of LADM-based marine cadastres and assess how applicable LADM as a published cadastral data standard is to marine cadastres. Griffith-Charles and Sutherland (2014) examine the different issues that affect the construction of a 3D LADM compliant marine cadastre in Trinidad and Tobago, with both legal and technical considerations. A profile is proposed to extend the current LADM to incorporate juridical, fiscal, and marine components of the land administration together, incorporating the Social Tenure Domain Model, STDM (Lemmen, 2010), as well as valuing the informal parcels in order to uniquely define a profile for the country (Griffith-Charles et al., 2018).

Athanasίου et al. (2015, 2016, 2017) claim that the complexity of interests in marine space is similarly encountered in land and that the extension of cadaster functions from land to marine space is reasonable. They propose to organise the RRRs included in marine space and to develop a marine administration model, based on LADM, followed by a database implementation. They discuss how the legislation can be included into a marine administration system based on international standards, and how RRRs relating to marine space may be defined and organised. Furthermore, they propose several modifications to the S-121 Maritime Limits and Boundaries (MLB) Standard (IHO, 2018), which refers to the international standard for land administration, LADM (ISO, 2012), with the introduction of marine resources into the model, the integration of data on legal spaces and physical features through external classes, as well as the division of law and administrative sources. See Fig. 7.

4.3.4. Valuation

The valuation topic deals with the use of 3D cadastral data for real estate valuation. The data sources and geospatial analyses can be used to visualise value spatial distribution. The eight publications on valuation from the studied period were distributed rather evenly between the years. The authors of these publications represent countries such as the Netherlands, Turkey, Germany, USA, United Kingdom and Croatia. Half of the publications belong to the technical class, and the remaining half is divided equally between registration and organisational. No publication belongs to the legal main class.

Various aspects of valuation are dealt with in the 8 publications from the studied years. Tomić et al. (2012) examines the possibilities of mass real estate valuation based on a 3D Vector Terrain Model created from the digital cadastral map. They claim that data derived from the system can be used for better understanding and explanation of real estate value spatial distribution. Isikdag et al. (2014a), (2014b), (2015) analyse current valuation practices in some countries and explore the role of semantically rich 3D building models and 3D cadastres in relation to valuation and taxation. Furthermore, they investigate the utilisation of building/cadastral information models in derivation of valuation-related information and information requirements for valuation related to 2D and 3D geometries and rights, restrictions and responsibilities (RRRs) associated with land lots and buildings. One publication (Asiama and Voss, 2020) looks back at the development of valuation approaches in relation to cadastres, to interrogate the needs for a 3D property valuation approach.

Toppen (2016) describes why and how the 3D CityGML modelling standard can be used in real estate valuation and transaction applications. This is achieved by examining how (3D) Geographic Information Systems (GIS) in real estate is used, e.g. by using 3D city models to visualise information per building storey. Kara et al., (2018, 2020) study the use of 3D data for better property value estimation in the context of the LADM Valuation Information Model and to develop 3D valuation unit profiles. They examine which geospatial analyses, especially 3D analyses, that can be used to provide information about immovable properties including environmental and locational characteristics for

property valuation activities. Furthermore, they investigate how property valuation can benefit from data sources including semantically rich 3D building, city and cadastral models for deriving environmental and locational characteristics of property units, and to what extent it is possible and meaningful to include derived 3D characteristics of property units in valuation registries. Asiama et al. (2020) investigate the needs for a 3D property valuation approach in relation to cadastres with the independent 3D property as the basic unit and further need for research on valuation. See Fig. 7.

5. Classification of 3D cadastre topics in conferences

To be able to analyse the classification of 3D cadastre research in technical programmes and proceedings of major conferences focussing, in total or in part, on 3D cadastre, a study was made of the session topics of the 3D cadastre conferences that were held from the first conference in 2001 until the most recent conference in 2021. During the mentioned period, seven conferences were held, in 2001, 2011, 2012, 2014, 2016, 2018 and 2021. During the first years, the main topics were legal, technical, registration and organisational, separate or in different combinations. Other common session topics were visualisation, data models, data management, data sources and country approaches. From the 2014 conference, BIM, CityGML and LADM were introduced as separate session topics. From the 2018 conference, the session topics were more specified, including topics such as process models, infrastructure and utilities, indoor and spatial planning. In the 2021 conference, the session topics showed more focus on BIM and GIS. The coming 11th international FIG 2023 workshop on the Land Administration Domain Model and 3D Land Administration is a combined conference for 3D cadastre and LADM.

In the yearly conferences (working weeks) held by the International Federation of Surveyors (FIG), there are also presentations made on 3D cadastre issues, resulting in conference papers. These conferences are usually held each year, but a review was made of the conferences held during the same years as the 3D cadastre conferences (2001, 2011, 2012, 2014, 2016, 2018 and 2021). It can be noted that the number of sessions devoted to 3D cadastre issues increased during the studied time period. During the first years, 3D spatial information and case studies were common topics. The following years were devoted to technical aspects and 3D modelling. From 2014 and onwards, BIM and GIS were reflected in the session topics, and it could be noticed that 3D cadastre presentations were included also in other session topics, not devoted to 3D cadastre issues. In 2018, presentations were made on best practices in different areas of 3D cadastre, while in 2021, there were a number of sessions devoted to a special workshop on LADM/3D Land Administration.

6. Discussion

The purpose of the paper is, as mentioned, to investigate current trends in 3D cadastre research in addition to the research published in 2012–2020 by Paasch and Paulsson (2021a) (2021b). The distribution of publications between the four categories in 2021 was found to be similar as during the years of the previous study, with the technical class in majority and in total the same as all the other categories together. In the secondary category, the results are more evenly distributed, which can be related to the fact that many publications with a technical focus also present some of the other aspects, but often as a background or addition to the main theme.

6.1. Visualisation, LADM and Other standardisation

This study shows that there has been an increase in the number of publications in each topic during the investigated years. There are publications on visualisation, LADM and other standardisation within all four categories, but nothing on other standardisation in the

registration and organisational categories during the last years. This is an area where new research could produce new knowledge beneficial for the research community. Cadastral information, such as real property boundaries, has traditionally been displayed in 2 dimensions and visualisation of 3D cadastral systems is an emerging field, even if there has been an increase in publications during later years. Visualisation is related to other categories and topics analysed in this research, for example legal issues and BIM. Visualisation is challenging in many ways, for example legal rights, restrictions and responsibilities often, but not always, have the same outline as a construction detail, e.g. a wall in a building. The boundary may be located outside or inside the wall and perhaps even pass through it.

LADM has been the subject of numerous publications after its formal publication as an ISO standard in 2012. There have however been publications on the subject prior to standard's publication, see e.g. Lemmen (2012), but the Paulsson and Paasch (2013) survey did not include LADM in their classification. It can be argued that the "introductory decade" of LADM, where focus was on how to use this new tool to describe land administration, is over and that the standard has become a well known tool in the research community. An example is the aforementioned International FIG Workshop on 3D Cadastres being renamed to "Workshop on the Land Administration Domain Model/3D Land Administration", being changed to a combined 3D cadastre and LADM workshop in 2023.

The reason for why no publications on the other standardisation topic have been identified to belong to the registration or organisational categories may be that cadastral research has to a large extent been focussing on technical and legal issues. Standards used in the technical category are to a large extent concerned with for example the ISO 19100 series of geographic information standards. Cadastre and land use is much concerned with the (legal) use of land, i.e. to connect a legal entity to a geographical place. Other standards are e.g. more data structure oriented, such as Geographic Markup Language, GML and other standards closely related to for example GML.

6.2. BIM, 4D cadastre, marine and water applications, valuation

Of the four topics described in this section, BIM accounts for the same number of publications as 4D cadastre and marine and water applications together, while valuation topics has the smallest number of publications, see Fig. 7. BIM is a popular topic in many fields of research at the moment and therefore the larger number of publications is not surprising. Since BIM is a rather new process that has increased in several different areas in recent years, it can be considered a new development. Valuation, 4D cadastre and marine and water applications are not new phenomena and have been subject to research before, but mainly not that much related to 3D cadastre.

Research on 4D cadastre has only produced a low number of publications during the investigated period, with an exception of 2021, where the yearly output has more than doubled, in line with the increase of the total number of publications during that year. It is however not possible to draw any conclusions because of the low number of publications, regarding whether it is a coincidence or the beginning of a new trend in cadastral research, where more research is carried out on the 4D cadastre topic.

Marine applications may not be that interesting for countries not in need of a marine cadastre, but the growing interest in managing the seas, e.g. focussing on climate change and sustainability, makes us assume that we can expect an increased number of publications on that topic as well, subject of interest in the 3D cadastre community, judging from the identified publications. Valuation issues might be discussed more in other research communities than specifically related to 3D cadastre.

There are also sub-topics within the investigated topics, such as marine cadastre, which is a specialisation of marine and water applications. It is not clear how the contents of such a topic can be classified - e.g. as technical (such as how to build a cadastre), legal (such as the legal

content and framework for a marine cadastre), registration or something else, or a combination of categories. We believe that classification of aspects have become much more complex today than before when introducing the rather wide legal, technical, registration and organisational categories first used in Paulsson and Paasch (2013) almost ten years ago.

Only a rather limited number of countries are involved in the four new research topics analysed in this paper, but the number of publications is too small to do any further analysis of the geographical distribution. However, based on the number of publications, there are several different countries involved and not just the same authors contributing to most of them. Examples of such countries are the Netherlands, Australia, Turkey and Sweden.

The identified new research areas seem to have gained interest in recent years and resulted in more publications on these topics. Among these topics can be found issues relating to new technology and standards, such as BIM, LADM and visualisation. BIM is a new topic and not found in the data from the earlier survey by Paulsson and Paasch (2013). One reason for why BIM related publications have emerged may be that building information modelling is a research and development topic mainly outside the 3D cadastre community in e.g. the geospatial and building industries and thus a driving force for the development of 3D cadastre applications and research.

6.3. Is there a 3D cadastral domain?

The variety of topics concerning the content and nature of 3D real property research, together with the keywords used in this analysis and some of the earlier mentioned studies, generates a question whether there is a single and identifiable "3D cadastral domain".

The majority of publications have been found in specialist 3D cadastre conference and workshop proceedings as well as in peer review journals focusing on land administration topics. Others have been included in non-3D cadastre theme specific conferences, such as BIM and LADM conferences, i.e. not treated as a specific 3D cadastre topic.

This research identified several publications which traditionally may not have been connected to 3D cadastre, such as conflict resolution and solar energy. A subject for future discussions is therefore whether it is a suitable term for the research domain or too general. There seems to be a change within the 3D cadastre community not to focus on the term 3D cadastre, but to use the term "3D land administration" instead. An example of this is the coming International FIG Workshop on 3D Land Administration in 2023, being the latest workshop in a series called 3D Cadastre workshops in the past.

In previous research conferences, there have often been devoted separate sessions to 3D cadastre research. Recently, however, there seems to be a tendency to include 3D cadastre aspects in sessions on other topics such as BIM and LADM. It seems like 3D cadastre is more applied to other areas and not studied as a separate research area. This might be due to the fact that 3D cadastre has been in use for quite a few years now and that the basics have already been researched. Instead, other ways of applying this and involving it into other areas have been found. BIM, visualisation, the use of LADM and other standards such as IFC show the same tendency and have also increased during the investigated period.

It can, in our opinion, be discussed if standardisation 3D cadastre research is to be regarded as a specific topic/group/field or rather a wide area of related research fields. We see similarities to LADM, which is a standard which since its creation in 2012 has been subject for a multitude of research activities and conferences. Standardisation of land administration is a huge concept and the forthcoming revised version of LADM is planned to cover other themes than the present version, such as valuation as mentioned above. We may therefore in the future not talk about a single 3D cadastre domain in general terms, but rather refer to specific parts of 3D cadastre research, covering more than one domain.

6.4. Trends in 3D cadastre practice

There have during several years been a world-wide inventory of 3D cadastre compiled from Fig. 3D cadastre questionnaires in 2010, 2014, 2018 and 2022, where a number of countries have answered questions related to the current status of 3D cadastre as well as the plans and expectations for the near future. The results of the most recent questionnaire in 2022 have not been published yet, but Schnaidman et al. (2019) have presented and analysed the results from the 2018 questionnaire.

Schnaidman et al. mentioned that from previous questionnaires, there are obstacles related to legislation or technological and organisational impediments to achieve a fully operational 3D cadastre. It can be noted from the questionnaire that the countries that have responded face different challenges. Among them can be mentioned LADM, real property taxation, BIM, visualisation, legal aspects and organisational aspects, which correspond with several of the research issues and trends that are found in the literature survey presented in this article. Schnaidman et al. (2019) present a few pilot projects related to some of the issues, e.g. the creation of 3D building models for visualisation purposes in Turkey, registration of Delft's railway station (transportation infrastructure) and registration of 3D above ground infrastructure in Malaysia. Among the countries' expectations for 2022 were mentioned registration of underground network legal objects with above surface segments as 3D objects, introduction of LADM-based formal 3D models, 3D cadastral systems based on LADM and other ISO and OGC standards, 3D Marine boundaries, legal amendments, etc. Schnaidman et al. (2019) mention ongoing efforts aiming at improving the capabilities of the digital cadastre in terms of storing, visualisation and dissemination of 3D related data, modernization of the legal system, developing a formal primarily LADM-based model and the marine cadastre, which seems to be in line with the current research trends.

The article has presented some identified trends without making any judgments whether or not these are the right research topics to focus on or presenting any recommendations on where future research should be heading. In one of the previous surveys (Paulsson and Paasch, 2013), recommendations on increased legal research were made and possible legal aspects to focus on in future research were proposed. Changes in research issues will be made along changes in society and arising challenges, although the direction for where the research trends are heading might be influenced by for example research calls, special issues in journals, conference themes or sessions, etc.

The themes of the international 3D cadastre workshops have during the last two decades incorporated a variety of topics ranging from registration, data modelling, standardisation, legal aspects of 3D cadastre and national implementation of national 3D real property. They have mainly a focus on technical and registration aspects and to some extent on legal issues, but very limited attention has been given to organisational issues. There seems however to be a shift towards a broader view combining 3D and land administration. Examples are the FIG Workshop 2021 and the coming FIG workshop 2023 on LADM/3D Land Administration aiming at a wider concept of 3D land administration and LADM research.

7. Conclusions

The research presented here indicates that there seems to be an increased interest for the presented themes, especially during recent years, but that it at the same time is too early to say whether they all are part of trends in 3D cadastre research or whether they are only expressing temporary interests as such for the 3D cadastre research community.

The paper is a literature survey and has no intention of finding solutions to the mentioned issues, which would rather be a topic for future research. Considering the development of 3D cadastre research and its alignment with other more general topics and fields, it might be

discussed whether we can talk about 3D cadastre (or any similar term representing that field) research as an overall comprehensive term for the research field, since this field has grown to be rather wide and large.

We hope that our results can be an input and inspiration for others on what topic or subtopic to focus on, with for example national 3D cadastre solutions and comparative analyses in the wide field of 3D cadastre in the future.

7.1. Further studies

Further research could include looking more deeply into some of the areas that were identified in the literature survey as developing areas with increased research. More comparative research would also be of benefit, involving more countries that could have an interest in 3D cadastre related to these areas. Since there is a rapid development within this research area, in particular related to digitalisation issues, a follow-up study of published research and new trends could also be of interest. This could be aligned with results from the future Fig. 3D cadastre questionnaires.

Declaration of Competing Interest

The authors have not submitted the paper to any other journal or third party and have no conflicting interests.

Data Availability

The authors are unable or have chosen not to specify which data has been used.

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