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Pregled raziskav na področju 3D katastra / A review of research on 3D real property cadastre

Tekavec, J., Ferlan, M., Lisec, A. (2018)

Geodetski vestnik, 62(2): 249-278

DOI: 10.15292/geodetski-vestnik.2018.02.249-278

Faktor vpliva za leto 2019: 0,469 (Q4)

PREGLED RAZISKAV NA PODROČJU 3D-KATASTRA NEPREMIČNIN

A REVIEW OF RESEARCH ON 3D REAL PROPERTY CADASTRE

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UDK: 347.2:528.44
Klasifikacija prispevka po COBISS.SI: 1.02
Prispelo: 3. 3. 2018
Sprejeto: 7. 5. 2018

DOI: 10.15292/geodetski-vestnik.2018.02.249-278
REVIEW ARTICLE
Received: 3. 3. 2018
Accepted: 7. 5. 2018

SI | EN

IZVLEČEK

3D-kataster nepremičnin (krajše 3D-kataster) je eno izmed pomembnih interdisciplinarnih raziskovalnih področij, na evropski in širši mednarodni ravni. Prve teoretične razprave segajo v 90. leta preteklega stoletja in se v začetku novega tisočletja še krepijo. Takrat so se oblikovali prvi mednarodni forumi za spodbujanje raziskav in oblikovanje teoretičnih zasnov 3D-katastra nepremičnin, ki jih je mogoče uveljaviti v praksi. Za spodbujanje sodelovanja med različnimi raziskovalnimi pobudami na širokem področju 3D-katastra je bila pri mednarodnem združenju FIG oblikovana delovna skupina za 3D-katastre. Pod okriljem FIG-a se je do danes zvrstilo pet tematskih delavnic oziroma mednarodnih forumov. Namen prispevka je podati kronološki pregled raziskav na področju 3D-katastrov s predstavitvijo objav, ki so pomembno usmerjale razvoj tega področja. Glavni vir so bile objave na mednarodnih forumih organizacije FIG, doktorske disertacije in znanstvene objave v mednarodnih revijah, katerih članki so opremljeni z digitalnim identifikatorjem DOI. Z raziskavami so bila v dveh desetletjih rešena številna pereča vprašanja, a obenem se pojavljajo nova, kompleksnejša vprašanja, predvsem povezana z uveljavitvijo 3D-konceptov v katastrskih sistemih posameznih držav, z večnamensko uporabo vsebinsko bogatih in kakovostnih 3D-katastrskih podatkovnih zbirk ter z združevanjem različnih prostorskih podatkovnih nizov v okviru 3D-katastra.

ABSTRACT

The 3D real estate cadastre ('3D cadastre' in short) is an important interdisciplinary research topic at both the European and international levels. Initial theoretical scientific discussions on the 3D cadastre began in the 1990s and gained momentum at the turn of the millennium, when the first international forums were organised. Their principal aim was to develop the theoretical concepts for the 3D cadastre that would foster the research activities and their implementation. At the time, the FIG Working Group on 3D Cadastres was formed to connect the research activities in the field. To date, five international thematic workshops have been organised. This article aims to provide a chronological overview of research activities by highlighting publications that have had a significant impact on 3D cadastre research. Our main sources have been publications at the FIG international thematic forums, doctoral dissertations, and papers published in scientific journals (included in the DOI system). Many issues and challenges have been resolved, and major progress has been seen in the past two decades. Nevertheless, numerous new complex issues have arisen, particularly regarding the realisation of 3D concepts within cadastral systems in the various countries, the idea of a multipurpose 3D cadastre, and the integration of various spatial datasets within a 3D cadastre.

KLJUČNE BESEDE

kataster, nepremičnine, 3D-kataster, zemljiška administracija, LADM

KEY WORDS

cadastre, real property, 3D cadastre, land administration, LADM

1 INTRODUCTION

Urban development coupled with increasingly complex cases of spatial delineation in terms of ownership and other property rights requires a new approach in land administration, which allows for registering and changing of property units, and associated information, in three spatial dimensions. The increasing physical and legal complexity of the built as well as natural environment necessitate an upgrading of the two-dimensional spatial modelling approach, which is conventionally used in national land administration systems.

The land administration domain has always been highly demanding in research terms at the international level, as countries developed their own systems underpinned by their historical background concerning land administration, their legal system, social setting as well as social needs associated with spatial development (Zupan *et al.*, 2014). The requirement for international comparability and thus structured treatment of land, and the rights, restrictions, and responsibilities associated to it, stemmed from the growing needs to develop state-of-the-art solutions in land administration. A result of many international discussions in the field was the international ISO standard 19152:2012: *Land Administration Domain Model (LADM),* adopted in 2012.

The purpose of this paper is to provide a broad review of internationally recognised publications and thus present the evolution of the 3D property cadastre over recent decades. Based on these publications we analysed the topics that are currently the focus of international research undertaken in this field.

2 METHODOLOGY AND RESOURCES APPLIED

Researchers and developers in various fields are concerned with developing 3D cadastre concepts as well as technical and legal solutions for its implementation. They all focus on a very specific domain, i.e. real property cadastre, which thus brings together the latest progress achieved worldwide. The main resources for this study were the available resources and records of the Thematic Working Group on 3D Cadastres, established by the International Federation of Surveyors (FIG)[1], which back in 2001 organised its first international forum with a view to help to develop solutions in the 3D property cadastre. An important resource for our work was publications in two special issues of the international scientific journal *Computers, Environment and Urban Planning* from 2003 and 2013, respectively, where also an overview of discussions under FIG until 2012 (Oosterom, 2013) was published, and publications in *ISPRS International Journal of Geo-Information* with a special issue *Research and Development Progress in 3D cadastral systems* of 2017. Additionally, we reviewed relevant PhD researches and English papers that appeared in other international journals published with the well-established *Digital Object Identifier* (DOI). The *CrossRef*[2] reference linking service was used, which is one of the solutions that publishers use to create DOI and include journals into an extremely large international community of electronic scientific and professional publications (see also Koler Povh and Lisec, 2015).

3 RESULTS – OVERVIEW OF 3D PROPERTY CADASTRE DEVELOPMENT

The beginnings of intensified efforts to develop the 3D real property cadastre date back to 1994 when FIG Working Group 7.1 was initiated, which in 1998 published the vision of developing future cadastral

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[1] *Fédération Internationale des Géomètres: www.fig.net.*

[2] *CrossRef: www.crossref.org, last reviewed 10 January 2018.*

systems entitled *Cadastre 2014* (Kaufmann and Steudtler, 1998). This document underlined the role of the cadastre as an important stakeholder to support sustainable development and decision-making concerning spatial decisions. The document provides important definitions and, inter alia, instead of a parcel (parcel-based cadastre), introduces the more general term "(land) object" as the basic real property element to which rights, restrictions, and responsibilities apply. The cadastre should give enough information to provide a complete picture of the situation of land, legal security, and transparency regarding the rights, restrictions, and responsibilities associated to cadastral objects. The end of separating between descriptive and graphic representations in the cadastre and the introduction of computer modelling, replacing analogue cadastral mapping, were projected, both because of the rapidly developing information technology. These new definitions and orientations encouraged, among other things, the discussion on introducing the third spatial dimension into real property records.

3.1 Studies in 3D property cadastre between 2000 and 2010

The first results of the studies in the research domain of 3D real property cadastres, which strongly affected further international research efforts, were published at the turn of the millennium (Stoter, 2000; Stoter and Zevenbergen, 2001). The authors find that the 2D system to register the legal status of real estate objects in many cases does not provide enough legal security regarding the rights and restrictions on real property objects and it can also no longer satisfy other functionalities of the land administration system.

3.1.1 Early internationally recognised studies, discussions, and publications

The previously mentioned research work at the Delft University of Technology, the Netherlands, was an introduction to the first workshop on the topic of real property cadastres in 2001, organised by FIG, which sparked interest and strengthened the topic of 3D cadastres in the research sphere. The workshop introduced the classification of the research field into legal, technical, and organisational aspects, which have been preserved, almost without modification, to this day. The workshop featured presentations on land administration systems in individual countries, existing ways of solving complex cases of real property registration where there is a need for vertically stratified allocation of rights, and on possibilities for further development (Grinstein, 2001; Huml, 2001; Menda, 2001; Onsrud, 2001; Ossko, 2001; Rokos, 2001; Viitanen, 2001). Among them was the presentation of the then introduced Building Cadastre in Slovenia (Pogorelčnik and Korošec, 2001).

The conclusions were drawn by Lemmen and Oosterom (2003) as an introduction to the special issue of the international journal Computers, Environment and Urban Planning, which published selected papers from this workshop. In his work, Molen (2003) argues that changes in complex systems, such as that of the cadastre, always require organisational development of institutional conditions and that they need to follow technological progress. The dilemma, i.e. the difference between legal objects and objects representing physical structures in space, is particularly underlined. Onsrud (2003) presented a new regulation in Norway, which was being adopted at the time, allowing for registering 3D properties to settle rights and restrictions on "construction properties". The possibility of combining this regulation with the existing one, based on the condominium concept, was presented. Back then, the real property registration system in Norway was still completely based on 2D parcels, partially even in analogue form.

The author saw no real possibility in the near future to technically register legal 3D property units as 3D objects. A major challenge in 3D cadastres, which remains pertinent today, was how to efficiently model cadastral data in information systems, as reflected in several papers published in the aforementioned special issue (Billen and Zlatanova, 2003; Stoter and Ploeger, 2003; Tse and Gold, 2003). Tse and Gold (2003) propose using a Triangulated Irregular Network (TIN) to model geometry and topology of 3D cadastral objects, which they justify by the feasibility of the proposed solution. Billen and Zlatanova (2003) also study how to model spatial objects, with an emphasis on spatial relationships. Stoter and Ploeger (2003) present the ways of developing conventional systems towards a 3D cadastre.

The doctoral thesis by Stoter (2004) is the first extensive research work on the 3D cadastre, which comprehensively discusses its technical aspect, while also delving into its legal and organisational aspects. It presents several practical cases in the Netherlands, where the two-dimensional approach in land administration is no longer meeting the demands for transparent real property registration. By analysing the state of land administration internationally and a detailed analysis of selected countries, she found that up to the point no country had developed a system for 3D registration of property units; moreover, it was not actively developed anywhere. She underlined and made clear the rationale to introduce 3D cadastres in selected study cases. She particularly addressed modelling, administration, and presentation of data on real properties in a 3D environment. Furthermore, she discussed the capacity of information technology for establishing databases, solutions for 3D geometry storage, procedures for validating the accuracy of the information recorded, and data administration functions of the time. In her research for her doctoral thesis, she developed three cadastral data models. The first one is an upgrading of existing cadastral systems, by storing links to 3D data, which are stored separately. The hybrid model preserves the existing role of the traditional 2D cadastre as the basis onto which rights, restrictions, and responsibilities are bound, but it allows for registration of 3D objects to show more clearly the situation regarding rights and restrictions in space in special cases. The real 3D cadastre allows for registration of volume parcels. 3D parcels assume the role of cadastral objects – the parcels in the cadastre are no longer defined as 2D polygons, but rather as 3D bodies, while in the case of traditional parcels lacking the vertical division they are defined as upright towers, which are not vertically limited. Hence, this is a volumetric division of the entire space with 3D property units.

Here, the activities of the United Nations Economic Commission for Europe should be mentioned, which in 2004, to support the development of efficient land administration systems, published guidelines focusing on real property units and object identifiers (United Nations Economic Commission for Europe, 2004), which importantly underlines the role of modern cadastre from the economic viewpoint. This document should help to align terminology and understand the differences between the systems of individual countries, facilitating international collaboration and data exchange in the field. It also touches upon the problem of the third spatial dimension of real property units, the condominium or strata title, and mineral extraction sites.

3.1.2 3D cadastre and data models

Rather than introducing the storage of the additional spatial dimension, the introduction of the 3D cadastre entails radical changes of the entire cadastral data model. The start of 3D cadastre development in the late 1990s coincides with the intensive period of introducing computer modelling in land administration as well. In 2003 the first proposal for a cadastral data model[3] was proposed to unify the concepts and data models of national systems (Oosterom and Lemmen, 2003). 3D cadastre is highlighted as a special case, defined as a possible upgrade or extension of the CCDM, along with the temporal aspect (Oosterom, Lemmen and Molen, 2004). In the latter case, the authors refer to the study by Stoter (2004).

3D models of physical objects (buildings and infrastructure) are not included into the Core Cadastral Domain Model (CCDM), but they are included into the set of relevant and related topics. The primary guidelines in developing CCDM are the inclusion of a maximum range of common characteristics of cadastral systems worldwide, as set out in *Cadastre 2014* (Kaufmann and Steudtler, 1998) and specified in international standards (Oosterom *et al.*, 2006). Great attention was given to the determination of its thematic scope; the authors developed CCDM in a very narrow manner but at the same time predicted the option of various thematic extensions. Such design facilitates the adjustment of the model to various systems around the world and at the same time preserves the basic level of comparability, i.e. common characteristics of cadastral systems. Further development of the model made it possible to include 3D parcels using the concept of bound surfaces, but with the limitation, i.e. that the area in question is recorded exclusively either in 2D format or 3D format. CCDM was the predecessor of the LADM model[4]. This new name of the model was first mentioned in 2008 (Groothedde *et al.*, 2008). FIG proposed the model to become an ISO standard (Lemmen, Oosterom and Uitermark, 2009) and since 2012 it has been officially published as ISO 19152:2012 standard (LADM, 2012).

In the initial period of research activities concerned with 3D property cadastre, studies and analyses of 3D geo-objects to be used in the 3D cadastre were carried out (Billen and Zlatanova, 2003; Tse and Gold, 2003). Stoter and Oosterom (2002) present the possibilities of modelling geo-objects in DBMS, providing the basis for managing cadastral systems from the perspective of information technology. Studies discuss management of 3D geo-objects in DBMS[5] in terms of modelling, functionality, and visualisation (Zlatanova, 2006; Khuan, Abdul-Rahman and Zlatanova, 2008). 3D objects can be represented as tetrahedrons, polyhedrons, and multipolygons. In these papers, authors argue that 3D geo-objects can, indeed, be stored, as DBMSs support the storage of spatial features, such as points, lines, and polygons in 3D space, but difficulties arise in terms of their administration, analysis, transmission, and visualisation. These problems stemmed from the fact that, at the time, DBMS did not yet support the data type of volumetric 3D objects and thus did not allow for management of such data and analyses in a 3D environment.

The checking of compliance of data with their formal definition is one of the most important aspects of data management; this also refers to 3D spatial data (Kazar *et al.*, 2008; Ledoux, Verbree and Si, 2009). This is highly significant in reference to 3D cadastres as well (Karki, Thompson and McDougall, 2010). Rather than focusing on the internal validity of individual objects, the authors addressed them in the context of a 3D cadastral system, where interrelationships between 3D objects and 2D parcels are important.

Time, i.e. the temporal aspect, as the fourth dimension of reality, is among the key cadastral data components. The first explorations in this field (Oosterom *et al.*, 2006) deal with time-sensitive cases and focus

[3] *Core Cadastral Domain Model (CCDM)*
[4] *Land Administration Domain Model*
[5] *Database Management System (DBMS)*

on the meaning of adding the temporal component to the cadastral data model, regardless of it being a 2D or a 3D cadastre. The temporal aspect is also addressed in the framework of the LADM standard that was proposed at the time (Döner *et al.*, 2008) and investigated on the case of registering underground infrastructures in various countries. The authors establish the relationship between the legal object and the physical object of underground utility networks by buffering, and at the same time distance themselves from registering the geometric description of the physical object in the cadastre. Notably, the authors argue that land administration systems have from the very beginning dealt with three dimensions as well as the temporal dimension within the current technical structure, i.e. as attributes. The temporal part of the data model is thus based on registering situations in time, i.e. "snapshots", which is basically done in most cadastral systems, or registering the initial situation and all ensuing events.

3.1.3 Legal aspects of the 3D cadastre

In early investigations on the 3D property cadastre, the legal topic was given significant less consideration than studies focusing on information technology. The first comprehensive and extensive study concerned with the legal aspects of the 3D property cadastre in the broader international context was done in Sweden (Paulsson, 2007), where the author dealt with the basic problem of defining a 3D property unit. With the purpose of universality, she defines it as a spatial unit that is delimited both horizontally and vertically. She divides rights, restrictions, and responsibilities, which are distributed in space, into condominium ownership, i.e. strata title, and independent 3D areas of rights. The strata title is treated as an established means of settling rights, which are delimited both horizontally and vertically, and therefore it is thoroughly examined in this work. The author comprehensively and systematically examines, and compares, four selected legal systems, which have different traditions and use different property right registration procedures in terms of their horizontal and vertical division: Germany with its traditional system of strata-title ownership and codified law, Sweden with a detailed legal system and new legislation allowing for registration of independent 3D property units, and Australian federal states New South Wales and Victoria, with ordinary law and legislation allowing for establishment of both strata title and independent 3D property units.

3.1.4 Organisational aspect – 3D cadastre situation and perspectives

Many publications from the first decade of intensified research on 3D property cadastres represent the situations and perspectives of introducing the 3D property cadastre in the individual countries. Most of them analyse the existing cadastral systems from their legal and technical aspects, complex cases where property registration should be tackled in three dimensions, and the options of 3D cadastre introduction in individual countries. These include specific conceptual designs, nevertheless, in all cases the technical solutions are, for the time being, practically not yet directly applicable.

The possibilities of 3D cadastre establishment were studied in Israel (Benhamu and Doytsher, 2003), where solutions were sought on the principle of multi-layered cadastres, which could contain, along with the data layer for traditional parcels, the data layers for structures above and below the surface (Benhamu and Doytsher, 2001; Benhamu, 2006). Technical challenges, related to Israel and beyond, were discussed by Peres and Benhamu (2009), when the efforts towards operational[6] implementation of

[6] *In this paper, the term "operational" refers to the actual use/implementation of something in the cadastral system of a certain country.*

3D cadastre had already strengthened. It is also worth mentioning China, where private property can be established on built structures only. Tang and Yang (2009) developed a conceptual model to enable registration of 3D property units, while recognising that, at the time, it was not yet feasible due to the lack of data and non-existent information and technological solutions for storing and managing 3D data. The literature reveals that Australian federal states New South Wales, Victoria (Paulsson, 2007), and Queensland (Stoter, 2004) have a tradition of a particular statutory scheme and registration of 3D property units. These can also apply to non-built-up areas above or below the Earth's surface. From the perspective of storing data on property unit geometry, the property registration system in all the federal states mentioned was entirely based on 2D concepts.

In this period Norway adopted legislation allowing for establishment of independent 3D property units (Valstad, 2010). The basic characteristics of this legislation were previously addressed by Onsrud (2003). Registration of independent 3D real property units is possible only for the purpose of registering engineering objects (Valstad, 2006), similarly as in Sweden (Eriksson, 2005; Paulsson, 2007). The cadastral system in both countries technically did not allow for digital registration of 3D geometry of property units. Registration of a single apartment as an independent 3D unit is not possible neither in Sweden nor in Norway. For this, the condominium registration has to be used, which regulates relationships between individual property units of a building. It should be underlined that both countries have a single land administration system, which was years ago established by combining the former dual system (legal and technical). This fact is stressed because of the organisational and institutional aspects of introducing the 3D cadastre and other major changes into land administration.

Contrary to the previously mentioned countries, which are in this period addressed more often due to their way of managing and registering 3D property units, the Netherlands kept the traditional organisation of its cadastral system. For several decades, the Netherlands has had a single land administration system inside one organisation (previously it had a dual system consisting of a land cadastre and a land register). The fact that the Netherlands frequently comes up in studies is the result of Dutch researchers' efforts and collaboration of the academic sphere and the surveying administration, which at the beginning of the decade greatly accelerated studies into 3D cadastres (Stoter and Ploeger, 2003; Stoter and Salzmann, 2003; Stoter, 2004).

In the first decade, by introducing the Building Cadastre, Slovenia set the basis for developing the 3D cadastre (Pogorelčnik and Korošec, 2001; Rijavec, 2009), but to date there have not been any major steps taken in this direction, while a major problem is also the poor link between land parcels and buildings, deficiencies in cadastral recording of engineering structures and infrastructural works (that are not buildings), and the insufficient data model of the Building Cadastre (see also Drobež, 2016; Drobež *et al.*, 2017).

In terms of operational implementation of the 3D real property cadastre in practice, the literature at the end of the decade often highlights that further development in all relevant fields is necessary, with the exception of the legal field in some countries, where there are practically no legal constraints. Interestingly, the study by Çağdaş and Stubkjær (2009), analysing methodological approaches used in doctoral researches concerned with cadastral system development, does not recognise the 3D cadastre nor the aforementioned doctoral studies (Stoter, 2004; Paulsson, 2007) as an important part of modern cadastre development.

3.2 Studies concerned with the 3D cadastre after 2010

In 2011 a survey was conducted among the members of FIG Working Group on 3D Cadastres, with 36 member states of this group taking part (Oosterom *et al.*, 2011). The survey's content focused on inventorying the situation by countries in 2010 and their expectations for 2014. The results of the survey importantly contribute to studies on 3D cadastres, as they allow free access to the extensive set of data on cadastral systems in many countries. The authors of the survey find that countries have different cadastral systems, where the incongruent perception of the 3D cadastre stems from. The differences are mostly regarding the understanding of the connection of traditional 2D parcels and 3D property units with physical structures. By the time no country had developed the system for storing and managing 3D data on property units in cadastres. Most of them were highly restrained in their plans and expectations for 2014. In 2014 representatives of 31 replied to the second, updated survey on the condition and expectations in 3D cadastre for 2018 (Oosterom, Stoter and Ploeger, 2014). In all countries, where the legal system allowed for registration of 3D property units, the ways of data registration, storing, and management were still based on 2D cadastre. What the countries had in common was that digital cadastral databases were mostly "incongruent" with the standard scheme ISO 19152:2012 (LADM, 2012). China stands out in terms of storing 3D data in digital format, stating in the replies to the survey that their database allows for storing, validating, and managing the 3D geometry of property units. Nevertheless, In the Chinese case we find an extremely small total number of parcels given the size of the country, so we assume that this situation is valid only for limited (urban) areas of China. Later studies (Guo *et al.*, 2013; Ho *et al.*, 2013; Dimopoulou, Karki and Roič, 2016; Stoter *et al.*, 2017) also confirm that at the beginning of the decade China did not have a fully operational 3D cadastral system.

In 2011, the second workshop on 3D cadastre took place in the Netherlands, 10 years after the first one. Interestingly, the next, third, workshop was planned to take place in two or three years, but it was held the very next year, which shows the growing international interest in research and knowledge exchange in this field. The report from the 2011 workshop (Banut, 2011) breaks down the situation in individual development fields of the 3D cadastre, divided into legal aspects, first registrations of 3D property units, administration of 3D spatial data and visualisation, transmission of data, and accessibility of data on 3D property units:

– The problem of terminological incongruency and various definitions of 3D cadastre was highlighted in the legal field.
– More than two thirds of the papers at the 2011 workshop describe land administration systems and different regulations for vertical stratification of property units from the perspective of current studies and data models.
– The field of managing digital 3D spatial data, particularly the fields of analyses and operations in DBMS and GIS[7], has been strongly lagging behind the field of 3D visualisation of spatial data, which made strong progress in the first decade of this millennium. The importance of electronic accessibility of 3D property cadastral data and 3D web-based visualisation techniques is underlined.

The thematic focus of the third workshop in 2012 was development and best practices in 3D cadastre (Oosterom, 2012). The need for more studies and comparative analyses of legal schemes in various coun-

[7] *Geographical Information System*

tries and the requirement to use existing standards, both in terms of modelling property units (LADM) and modelling physical spatial structures in land administration information systems, were expressed. Inter alia, the meaning of visualisation of 3D property objects was stressed, as the needs and challenges are different than with visualisation of more commonly used 3D models of cities and landscapes.

Based on the papers from FIG workshops and conferences in 2011 and 2012, Oosterom (2013) provides an overview of development in 3D cadastres and presents the most important topics for further studies. We particularly underline the topics that remain topical at a global level today:

- As mentioned earlier, the lack of studies concerned with legal aspects was discussed by Paulsson and Paasch (2013) after reviewing 156 publications in English between 2001 and 2011. They identified the lack of terminological and comparative studies that would cover several countries and several 3D cadastre legal schemes.
- Heights and vertical systems in 3D cadastres were addressed in detail for the first time by Navratil and Unger (2013). They represented the general problems of vertical reference systems, restrictions, and demands of 3D cadastres, also on practical cases. The greatest attention is given to the analysis of strengths and weaknesses of using absolute and relative heights in the 3D cadastre.
- An important element, which greatly influences the dynamics of establishing the 3D cadastre, is its cost–benefit relationships. One of such studies, with reference to Trinidad and Tobago, found a positive cost/benefit ration in urban, densely populated areas and the oil mining areas (Griffith -Charles and Sutherland, 2013). The authors conclude that it is reasonable to explore the possibility of introducing the 3D cadastre in selected areas only, where benefits exceed costs.
- Operational implementation of 3D cadastres, inter alia, requires the specification of clear rules regarding division of space into 3D property units, their modelling in the 3D environment, and, at the same time, coupled with validation procedures as to their compliance with the rules set. This is much more difficult in three spatial dimensions, as the set of rules is more extensive and the procedures of compliance verification are more complex than in the conventional 2D cadastre. Karki, Thompson and McDougall (2013) thoroughly studied this field and developed specific solutions and a set of challenges and questions that remain to be solved. They conclude that the development of land administration systems towards the 3D cadastre is not possible in a short period of time. One of the solutions is the gradual adaptation of existing systems, as argued by Guo *et al.* (2013). On the case of the Chinese cadastre, authors stem from the existing legal system and the 2D cadastral data model, into which they include elements of the 3D cadastre. This paper is also interesting when compared to the results of the previously mentioned research on 3D cadastre development by Oosterom, Stoter and Ploeger (2014), where we could have made the wrong assumption the China had had a fully operational 3D cadastral system before 2014.
- The comparison of cadastral systems of various countries is difficult due to their diversity. Pouliot, Vasseur and Boubehrezh (2013) compared cadastral system models in France and Canada with a focus on the third spatial dimension based on the LADM standard (2012). They identified, as the most demanding part, the transformation of the data model of the individual system into the standard LADM scheme, which then allows for direct comparison between various cadastral systems, their classes, and attributes. They propose and justify the inclusion of volumetric geometry in the standard, which would increase the applicability of the LADM standard in the 3D cadastre as well.

The papers in the fourth FIG workshop on the topic of 3D cadastre in 2014 were mostly technically oriented, regardless of the voiced concerns about the lack of consideration of the legal problem (Paulsson and Paasch, 2013):

- At the workshop, the legal aspect was addressed as a main topic only in one presentation, on the case of the national study for Poland (Karabin, 2014).
- There was a growing consideration of the ISO standard LADM (2012) and the open standardised data model CityGML by OGC[8] (CityGML, 2012), which were found, in a combination or separately, in eight publications. Compared to the previous workshops, the number of studies and presentations of national cadastral systems dropped. Two publications were particularly interesting (Almeida *et al*., 2014; El-mekawy, Paasch and Paulsson, 2014), as they discussed voluntary geographical information and linked BIM[9] solutions with the 3D cadastre. These two topics were presented as a challenge to the 3D cadastre, as both areas are intensively studied in the wider area of geosciences. Building Information Modeling (BIM) provides a potential for developing a 3D cadastre, and together they provide an important area for future research (Rajabifard, 2014).
- The content of publications shows the growing interest in studies on 3D visualisation (Navratil and Fogliaroni, 2014; Pouliot, Wang and Hubert, 2014; Ribeiro, de Almeida and Ellul, 2014) which is confirmed by two extensive doctoral dissertations from the period (Shojaei, 2014; Wang, 2015). Wang (2015) focused on evaluating the suitability of 3D model visualisations for the case of strata title, while Shoaei (2014) mostly analysed user requirements and needs.

3.2.1 Challenges related to the 3D cadastre from a legal perspective

Even though the legal aspect of the 3D cadastre was not given significant consideration at the 2014 FIG workshop, this research domain remains topical at the international level. In land administration and property records the concepts of physical and abstract space meet, where rights, restrictions and responsibilities are associated to "abstract" spatial units. With incomplete knowledge of the field they can be equated based on coincidence of boundaries of physical structures and rights, i.e. restrictions in some cases. The division of space from the legal aspect is fundamentally abstract, while its link with physical space is established in various forms and from various reasons, while it varies from one legal system to another. The 3D cadastre domain is mostly directed towards treating partitioning of buildings into property units, as a relationship between space of legal significance and physical space and its structures (Aien, 2013; Aien *et al.*, 2013, 2015) therefore physical boundaries are often equated with legal boundaries. In these studies, the authors developed the 3DCDM data model[10], which combines the physical and legal aspects of dividing space for the needs of the 3D cadastre.

The evolution of the 3D cadastre in the first decade led to discrepancies regarding legal definitions of a property in three dimensions (Paasch and Paulsson, 2012). The authors find that the latter causes problems also in research, where inconsistent definitions of basic terminology limit the possibilities of comparative analyses and studies. They emphasise that the legal definition of a property in three dimensions must be broad enough to be acceptable in most legal systems. Secondly, the definition must provide a clear and unique definition of the property and delimit it from the traditional property in two dimensions. The authors propose using a universal definition of 3D properties, as previously proposed by Paulsson (2007).

8 *Open Geospatial Consortium: http://www.opengeospatial.org/*
9 *Building Information Modelling*
10 *3D Cadastral Data Model*

Among interesting legally-oriented studies is that by Ho *et al.* (2013) where the authors argue that the significant barriers to 3D cadastre implementation lie not in technology, which is developed well enough, nor in legal systems, as in many countries, thay allow for registration of 3D property units – instead, there must be a limiting factor, inertia, preventing faster 3D cadastre implementation. Authors explain and break down this inertia by introducing the institutional theory and justifying that the reasons for slow changes lie in the slow adaptability within organisations responsible and the strongly rooted 2D concept in land administration systems. Oosterom and Lemmen (2015) stress that 3D (and 4D) administration are among the most significant development trends in land administration and thus also the LADM standard. They present the studies arising from the first thematic workshop after the publication of the LADM standard, among which two studies treat the topic of 3D cadastre development in Korea and Malesia (Lee *et al.*, 2015; Zulkifli *et al.*, 2015).

3.2.2 Challenges of introducing the 3D cadastre

A special topic in developing the 3D cadastre is its operational implementation. The first studies concerned with the topic were done under the Dutch project intended to help the transition to the 3D cadastre, which is based on two implementation phases (Stoter, Oosterom and Ploeger, 2012; Stoter, Ploeger and Oosterom, 2013). The first phase was to gain experience, adjusting its solutions to existing legal and technical frameworks. Its implementation part relates to the possibility of property registration based on a PDF document, which contains 3D geometry and is connected with other data about the property through a link in the database. The assessment of registration and system maintenance costs is interesting as, for new buildings, they should not be higher than the existing registration costs. Today, the first phase of implementing 3D cadastre allows for solving some complex situations, particularly to unambiguously show the division into property units, while the existing 2D land administration system basically remains the same. The second phase is far more ambitious, as it provides for 3D cadastre establishment, allowing for a comprehensive digital registration of property units, including geometry, in the form of 3D objects (volumetric bodies) directly in the cadastral database. Many issues arise in the second phase related to validation of 3D data geometries, required positioning and geometrical accuracy, data formats, inclusion of curved surfaces, partially open elements, etc. (Stoter *et al., 2017*).

The project of 3D cadastral modelling in Russia began in collaboration with Dutch researchers. They developed a prototype that mostly focuses on the manner of modelling and representing 3D property units. In their designs, they defined a pilot project in a small area, where they would approach the real implementation of registration. Vandysheva *et al.* (2012) underline the meaning of automated control during the entry of new property units in the sense of compliance with previously set rules. Despite the intensified efforts for 3D cadastre establishment and land administration system upgrade in recent years, the Russian cadastral system is still based on two spatial dimensions (Ilyushina, Noszczyk and Hernik, 2017).

3.3 Current topics and studies on the 3D cadastre

The last FIG workshop on 3D cadastre took place in 2016. The fact that this research domain is active is also proven by the increased number of papers (31) compared to the previous workshop (25). Extended papers were collected in a special issue of the international journal *ISPRS International Journal of Geo-Information* entitled *Research in Development Progress in 3D cadastral systems 2017*.

Most notable is the major body of research around the analysis of situations in individual countries and the different possibilities for developing land administration systems, particularly publications focusing on technical solutions of modelling 3D property units in land administration information systems (Araújo and Oliveira, 2016; Dimas, 2016; Soon, Tan and Khoo, 2016; Gulliver, Haanen and Goodin, 2017). Other publications in internationally renowned journals also touch upon this field. Aien *et al.* (2017) underline six of the most established data models in the cadastre, where, due to the differences in land administration systems, many data models have emerged. The authors particularly highlight three of them (LADM, ePlan, ArcGIS Parcel Data Model) and analyse them in detail in terms of their usability for 3D cadastres. Data model 3DCDM, which was as part of his doctoral research developed by the lead author, is not included nor mentioned in the study. The authors conclude that some data models discussed allow for modelling 3D property units, but each of them has important limitations for 3D cadastre development.

At the research level, the legal domain of studies is strongly represented (Kitsakis and Dimopoulou, 2017; Vučić *et al.*, 2017), headed by an extensive comparative study of selected countries (Kitsakis, Paasch and Paulsson, 2016; Paasch *et al.*, 2016). Kitsakis, Paasch and Paulsson (2016) present the legal definition of 3D property units in various countries (Austria, Brazil, Croatia, Greece, Poland, and Sweden) and the plans for future development. Of these countries, Sweden is the only one that does not restrict registration of 3D property units in its legal system; however, data management in Sweden, and elsewhere, is still based on 2D concepts.

Another interesting study, by Janečka and Souček (2017), is concerned with data modelling in management in 3D cadastres. The authors discuss the current situation in the wider area of 3D geoinformatics, which covers concepts, data models, standards, and operations related to 3D spatial data. The emphasis is on the current capacities of spatial databases in view of modelling and managing 3D spatial data. The connection or integration of BIM data with the 3D cadastre data model is extremely topical. In relation to BIM data, a growing number of studies is focusing on modelling indoor spaces of buildings for the needs of registering property units (Oldfield *et al.*, 2016; Atazadeh, 2017). Atazadeh *et al.* (2017) treat BIM as the basis for managing rights and restrictions associated to buildings. They propose the extension of the data model so that it could support the input of data on the rights and restrictions inside buildings and their management. Among other, the authors address the topical questions of relationship of 3D units of legal significance and a building's physical model. Along with strengths, the authors discuss the limitations of the proposed approach, which include institutional barriers, the too extensive data structure, and the discrepancy between the planned structure and the structure actually built.

The research by Zlatanova *et al.* (2016) is oriented towards modelling indoor spaces of buildings, where in 2014 the standard OGC – IndoorGML (2014) was used for the first time as part of the studies into the 3D cadastre. In this paper the authors discuss the options for linking the aforementioned standard with the LADM standard. Further research in this area was done by Alattas *et al.* (2017). The IndoorGML standard is based on a multi-layered space-event model, which was originally intended for indoor navigation, as proposed in 2009 (Becker, Nagel and Kolbe, 2009). This group of authors also led the development of CityGML, the previously developed standard for modelling cities and landscapes in the 3D environment. The IndoorGML standard introduces a cellular approach to modelling indoor spaces of buildings, using the duality principle (Munkres, 1984), coupled with mathematical graphs. It allows for the operation of the optimal path searching algorithms to support navigation as well as other algorithms based on topological relationships among the objects. The standard allows for extensions of the data model in the form of extension modules for various fields. Kang and Li (2017) particularly stressed the possibility of implementing the extension module of the IndoorGML standard to be used in the 3D cadastre. Linking outdoor city models and models of buildings' indoor spaces has been recognised as a research problem also by the United Nations Committee of Experts on Global Geospatial Information Management – UN-GGIM (2015).

4 CONCLUSIONS

The beginnings of introducing the term 3D cadastre date back to the publishing of the document *Cadastre 2014* (Kaufmann and Steudtler, 1998). To facilitate the materialisation of these goals, in 2001 FIG held the first workshop, which encouraged research into the 3D cadastre. The various aspects of developing 3D cadastres were set more clearly: legal, technical, and administrative, of which the first two are more strongly represented in studies. The first decade was characterised by many analyses of land administration systems in individual countries and proposals for their upgrading. They collectively concluded that additional development in all the mentioned research fields are needed to establish 3D registration.

Doctoral dissertation by Stoter (2004) left an indelible mark on the technical aspect of studying 3D cadastres. Most studies thereon related to her findings, definitions, and proposals. Two countries stand out in the legal field: Sweden, which in 2004 introduced the option of registering 3D property units in its legal system, and Australia with a longstanding tradition of possibilities to register independent 3D property units. The doctoral dissertation by Paulsson (2007) is among the most acclaimed studies into legal systems related to the 3D cadastre, providing a comprehensive review and insight into the legal aspect of the 3D cadastre. *Cadastre 2014* set off initial designs of CCDM to unify the key components of land administration systems, with open possibilities for including specificities, and characteristics of individual countries. This is the direct predecessor of the international standard LADM (2012), which basically does not restrict the evolution of the traditional 2D cadastre into the 3D cadastre.

The last decade of studies concerned with the 3D cadastre has been characterised by the publication of standards LADM (2012), CityGML (2012), and IndoorGML (2014). Most studies in this period study the possibility of using the standards, analyse the strengths and weaknesses of the individual standards and compare them, while fewer studies tackle the legal aspect, as previously found by Paulsson and Pasch (2013). During this time, Dutch researchers importantly contributed to implementing the concepts of the 3D cadastre into practice; in the future it will be interesting to see how a growing number of countries will decide to include the third dimension in the cadastre. Research challenges in 3D cadastres also relate to the integration of data from other domains, particularly research regarding the use or inclusion of BIM data in the 3D data model, and vice versa. The treatment or modelling of indoor structure of buildings is also topical; it is complex both from the aspect of data structure and complexity of data models as well as from the aspect of data acquisition and integration of models of indoor spaces and outdoor models of cities and landscapes (UN-GGIM, 2015).

Acknowledgements

This review article is the result of work undertaken under research programme No. P2-0227 entitled "Geoinformation Infrastructure and Sustainable Spatial Development of Slovenia", co-financed by the Slovenian Research Agency (ARRS) from the national budget.

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PREGLED RAZISKAV NA PODROČJU 3D-KATASTRA NEPREMIČNIN

OSNOVNE INFORMACIJE O ČLANKU:
GLEJ STRAN 249

1 UVOD

Urbani razvoj in z njim vse bolj zapleteni primeri razmejevanja prostora z vidika lastninske ali drugih pravic na nepremičninah zahtevajo nov pristop v zemljiški administraciji, ki omogoča evidentiranje in spreminjanje nepremičninskih enot ter z njimi povezanih podatkov v treh prostorskih razsežnostih. Vse večja fizična in pravna kompleksnost grajenega, pa tudi naravnega okolja narekuje nadgradnjo modeliranja prostora v dveh razsežnostih, ki je tradicionalno navzoče v nacionalnih sistemih zemljiške administracije.

Področje zemljiške administracije je bilo od nekdaj zelo zahtevno za raziskave na mednarodni ravni, saj so države razvile svojevrstne sisteme, ki so med drugim zelo pogojeni z zgodovinskim ozadjem zemljiške administracije, s pravnim sistemom in družbeno ureditvijo, pa tudi s potrebami družbe na področju upravljanja prostora (Zupan *et al.*, 2014). Zaradi vse večjih potreb po razvoju sodobnih rešitev na področju zemljiške administracije se je pojavila zahteva po mednarodni primerljivosti in s tem po strukturirani obravnavi zemljišč ter pravic, omejitev in odgovornosti (angl. *rights, restrictions and responsibilities*) na njih. Rezultat številnih mednarodnih razprav na tem področju je v letu 2012 sprejeti mednarodni standard ISO 19152:2012: *Land Administration Domain Model (LADM)*.

Namen prispevka je podati širok pregled mednarodno prepoznanih objav in s tem predstaviti razvoj področja 3D-katastra nepremičnin v preteklih desetletjih. Na podlagi obravnavanih objav smo analizirali aktualne raziskovalne teme, ki na mednarodni ravni oblikujejo osrčje raziskovalnega dela na tem področju.

2 UPORABLJENA METODOLOGIJA IN VIRI

S področjem razvoja konceptov 3D-katastra ter tehničnih in pravnih rešitev za uvedbo 3D-katastra se ukvarjajo raziskovalci in razvijalci z različnih področij. Skupno vsem je, da se osredotočajo na precej specifično domeno, to je kataster nepremičnin, ki tako združuje dognanja na svetovni ravni. Glavni viri za našo raziskavo so bili dosegljivi viri in zapisi tematske delovne skupine za 3D-kataster mednarodnega združenja FIG[1], ki je že leta 2001 organizirala prvi mednarodni forum, s čimer je želela prispevati k razvojnim rešitvam na področju 3D-katastra nepremičnin. Pomemben vir za naše delo so bile objave v dveh tematskih številkah mednarodne znanstvene revije *Computers, Environemnt and Urban Planning* iz let 2003 in 2013, kjer je objavljen tudi pregled vsebin razprav v okviru organizacije FIG do leta 2012 (Oosterom, 2013), ter objave v reviji *ISPRS International Journal of Geo-Information* s tematsko številko *Research and Development Progress in 3D cadastral systems* iz leta 2017. Dodatno smo pregledali doktorske raziskave s tega področja in angleške članke v drugih mednarodnih revijah, ki so objavljeni s

[1] *Fédération Internationale des Géomètres: www.fig.net.*

široko uveljavljenim označevalcem elektronske lokacije DOI (angl. *digital object identifier*). V ta namen smo uporabili iskalnik *CrossRef*[2], ki je ena izmed rešitev za založnike in omogoča kreiranje navedenega označevalca ter uvrščanje revije v izjemno veliko mednarodno družino elektronskih znanstvenih in strokovnih objav (glej tudi Koler Povh in Lisec, 2015).

3 REZULTATI – PREGLED RAZVOJA PODROČJA 3D-KATASTRA NEPREMIČNIN

Začetki izrazitejšega oblikovanja zamisli o 3D-katastru nepremičnin segajo v leto 1994 z začetkom delovne skupine 7.1 mednarodnega združenja FIG, ki je leta 1998 objavilo vizijo razvoja katastra pod naslovom *Cadastre 2014* (Kaufmann in Steudtler, 1998). V dokumentu je izpostavljena vloga katastra kot pomembnega deležnika pri trajnostnem razvoju in odločitvah v prostoru. V dokumentu so podane pomembne opredelitve, ki med drugim kot osnovni nepremičninski element v katastru namesto parcele (parcelno orientiran kataster) uvajajo splošnejši izraz, to je ‚objekt', na katerega so vezane pravice, omejitve in odgovornosti. Kataster naj bi tako celostno izkazoval stanje prostora ter zagotavljal pravno varnost in transparentnost glede pravic, omejitev in odgovornosti, ki se nanašajo na katastrske objekte. Napovedana sta bila konec ločevanja opisnih in grafičnih podatkov v katastru ter uvedba računalniškega modeliranja, ki nadomešča analogno katastrsko kartiranje, oboje kot posledica hitrega razvoja informacijske tehnologije. Navedene nove opredelitve in usmeritve so med drugim spodbudile razpravo o uvajanju tretje prostorske razsežnosti v nepremičninske evidence.

3.1 Raziskave na področju 3D-katastra nepremičnin v obdobju 2000–2010

Prvi rezultati raziskav, ki odpirajo raziskovalno področje 3D-katastrov nepremičnin in močno vplivajo na nadaljnjo mednarodno raziskovalno dejavnost, so bili objavljeni že na prelomu tisočletja (Stoter, 2000; Stoter in Zevenbergen, 2001). Avtorja ugotavljata, da registracija nepremičnin v dveh razsežnostih v številnih primerih ne prinaša zadostne pravne varnosti glede pravic in omejitev na nepremičninah, prav tako ne zadošča drugim funkcionalnostim sistema zemljiške administracije.

3.1.1 Prve mednarodno prepoznavne raziskave, razprave in objave

Že navedeno raziskovalno delo na Tehniški univerzi v Delftu na Nizozemskem pomeni uvod v prvo delavnico na temo 3D-katastrov nepremičnin v letu 2001, ki je bila organizirana pod okriljem zveze FIG, s tem pa se je razširilo zanimanje in utrdil položaj tematike 3D-katastrov v raziskovalni sferi. Uvedena je bila klasifikacija področja raziskav na pravne, tehnične in organizacijske vidike, ki se je v skoraj nespremenjeni obliki ohranila vse do danes. Na delavnici so prevladovale predstavitve sistemov zemljiške administracije posameznih držav, obstoječih načinov reševanja zapletenih primerov registracije nepremičnin, kjer obstaja potreba po višinski razdelitvi pravic, in možnosti za nadaljnji razvoj (Grinstein, 2001; Huml, 2001; Menda, 2001; Onsrud, 2001; Ossko, 2001; Rokos, 2001; Viitanen, 2001). Med njimi najdemo tudi predstavitev takrat uvedenega Katastra stavb v Sloveniji (Pogorelčnik in Korošec, 2001).

Ugotovitve z navedene delavnice sta predstavila Lemmen in Oosterom (2003) kot uvod v tematsko številko mednarodne revije *Computers, Environemnt and Urban Planning*, kjer so objavljeni izbrani

[2] *CrossRef: www.crossref.org, nazadnje pregledano 10. 1. 2018.*

prispevki z delavnice. Molen (2003) v svojem delu izpostavi, da spremembe kompleksnih sistemov, kot je kataster, vedno zahtevajo tudi organizacijske spremembe v institucijah in da morajo le-te slediti tehnološkemu napredku. Posebej je izpostavljena dilema oziroma razlika med objekti pravnega pomena in objekti, ki predstavljajo fizične strukture v prostoru. Onsrud (2003) predstavi novo pravno ureditev na Norveškem, ki je bila v procesu sprejemanja in omogoča registracijo 3D-nepremičninskih enot za potrebe ureditve pravic in omejitev na grajenih objektih. Predstavljena je tudi možnost kombinacije navedene ureditve z obstoječo, ki temelji na konceptu etažne lastnine. Takratni sistem registracije nepremičnin na Norveškem je še v celoti temeljil na 2D-parcelah, deloma celo še v analogni obliki. Avtor v bližnji prihodnosti ni videl realnih možnosti, da bi pravno veljavne 3D-nepremičninske enote tudi tehnično lahko registrirali kot 3D-objekte. Velik izziv, ki je še vedno aktualen na področju 3D-katastra, je bil način učinkovitega modeliranja katastrskih podatkov v informacijskih sistemih, kar se odraža v več objavljenih prispevkih navedene tematske številke (Billen in Zlatanova, 2003; Stoter in Ploeger, 2003; Tse in Gold, 2003). Tse in Gold (2003) predlagata za modeliranje geometrije in topologije 3D-katastrskih objektov mrežo nepravilnih trikotnikov, kar utemeljita z izvedljivostjo predlagane rešitve. Tudi Billen in Zlatanova (2003) se ukvarjata z načinom modeliranja prostorskih objektov, s poudarkom na njihovih medsebojnih povezavah. Stoter in Ploeger (2003) predstavita možne načine razvoja tradicionalnih sistemov v smeri 3D-katastra.

Doktorska disertacija Stoterjeve (2004) je prvo obširno raziskovalno delo na področju 3D-katastra, v katerem je celovito obravnavan njegov tehnični vidik, dotika pa se tudi pravnega in deloma organizacijskega vidika. Predstavi več primerov iz prakse na Nizozemskem, kjer dvorazsežni pristop v zemljiški administraciji ne zadovoljuje zahtev po pregledni registraciji nepremičnin. Z analizo stanja zemljiške administracije v mednarodnem okolju in podrobnejšo analizo izbranih držav je ugotovila, da takrat nobena država ni imela razvitega sistema za 3D-registracijo nepremičninskih enot, prav tako ta ni bil nikjer predmet aktivnega razvoja. Avtorica izpostavi in jasno utemelji potrebo po uvedbi 3D-katastra na izbranih študijskih primerih. Obravnava predvsem področje modeliranja, upravljanja in predstavitve podatkov o nepremičninah v 3D-okolju. Predstavljene so takratne zmogljivosti informacijske tehnologije za vzpostavitev podatkovnih baz, rešitve za shranjevanje 3D-geometrije, postopki za preverjanje pravilnosti zapisanih podatkov in funkcije za upravljanje podatkov. V okviru doktorskega raziskovalnega dela je avtorica razvila tri različne katastrske podatkovne modele. Pri prvem gre za nadgradnjo obstoječih katastrskih sistemov s shranjevanjem povezav do 3D-podatkov, ki so shranjeni ločeno. Hibridni model ohranja obstoječo vlogo tradicionalnega 2D-katastra kot podlago, na katero se vežejo pravice, omejitve in obveznosti, a dovoljuje registracijo 3D-objektov za namene jasnejšega prikaza stanja pravic in omejitev v prostoru v posebnih primerih. Pravi 3D-kataster omogoča registracijo prostorninskih parcel. 3D-parcele prevzamejo vlogo katastrskih objektov – parcele v katastru niso več opredeljene kot 2D-poligon, ampak kot 3D-telo – pri tradicionalnih parcelah brez vertikalne razmejitve pa kot pokončni stolpi, ki vertikalno niso omejeni. Gre torej za prostorninsko razdelitev celotnega prostora s 3D-nepremičninskimi enotami.

Tu velja omeniti še dejavnosti Ekonomske komisije Združenih narodov za Evropo, ki je leta 2004 z namenom podpore razvoju učinkovitih sistemov zemljiške administracije objavila dokument z usmeritvami, s poudarkom na nepremičninskih enotah in objektnih identifikatorjih (United Nations Economic Commission for Europe, 2004), ki pomembno izpostavlja vlogo sodobnega katastra z ekonomskega vidika. Dokument naj bi prispeval k uskladitvi terminologije in razumevanju razlik med sistemi posameznih držav ter tako omočil lažje mednarodno sodelovanje in izmenjavo podatkov na tem področju. Deloma se dotika tudi problematike tretje prostorske razsežnosti nepremičninskih enot, etažne lastnine in območij mineralnih surovin.

3.1.2 3D-kataster in podatkovni modeli

Uvedba 3D-katastra ne pomeni le uvedbe shranjevanja dodatne prostorske razsežnosti, ampak prinaša korenite spremembe celotnega katastrskega podatkovnega modela. Začetek razvoja na področju 3D-katastra konec devetdesetih sovpada z intenzivnim obdobjem uvajanja računalniškega modeliranja tudi na področju zemljiške administracije. V letu 2003 je bil z željo po poenotenju konceptov in podatkovnih modelov nacionalnih sistemov objavljen prvi predlog katastrskega podatkovnega modela CCDM[3] (Oosterom in Lemmen, 2003). 3D-kataster je izpostavljen kot poseben primer, ki je opredeljen kot možnost za nadgradnjo oziroma razširitev osnovnega katastrskega podatkovnega modela skupaj s časovnim vidikom (Oosterom, Lemmen in Molen, 2004). Pri slednjem se avtorji sklicujejo na raziskavo Stoterjeve (2004).

3D-modeli fizičnih objektov (stavbe in infrastruktura) niso vključeni v osnovni podatkovni model CCDM, so pa uvrščeni v sklop ustreznih povezanih vsebin. Primarna vodila pri razvoju CCDM so vključitev čim širšega obsega skupnih značilnosti katastrskih sistemov po svetu, upoštevanje izhodišč dokumenta *Cadastre 2014* (Kaufmann in Steudtler, 1998) in mednarodnih standardov (Oosterom *et al.*, 2006). Velika pozornost je bila namenjena določitvi njegovega tematskega obsega; avtorji so osnovni podatkovni model zasnovali zelo ozko in obenem predvideli možnost različnih tematskih razširitev. Takšna zasnova omogoča lažje prilagajanje modela različnim sistemom po svetu in obenem ohranja osnovno raven primerljivosti oziroma skupnih značilnosti katastrskih sistemov. Nadaljnji razvoj modela je prinesel možnost vključitve 3D-parcel ob uporabi koncepta povezanih površin, a z omejitvijo, da je posamezno območje evidentirano izključno v 2D- ali izključno v 3D-obliki. CCDM je neposredni predhodnik modela LADM[4]. Novo ime modela se pojavi v letu 2008 (Groothedde *et al.*, 2008). Zveza FIG ga je predlagala za ISO-standard (Lemmen, Oosterom in Uitermark, 2009) in je od leta 2012 uradno objavljen kot standard ISO 19152:2012 (LADM, 2012).

Že v začetnem obdobju raziskovalne dejavnosti na področju 3D-katastra nepremičnin se pojavljajo raziskave in analize 3D-grafičnih gradnikov, ki naj bi se uporabljali v 3D-katastru (Billen in Zlatanova, 2003; Tse in Gold, 2003). Stoter in Oosterom (2002) predstavita možnosti modeliranja grafičnih gradnikov v okviru SUPB[5], ki je osnova za upravljanje katastrskih sistemov z informacijsko-tehnološkega vidika. V raziskavah je obravnavano upravljanje 3D-grafičnih gradnikov v SUPB z vidika modeliranja, funkcionalnosti in vizualizacije (Zlatanova, 2006; Khuan, Abdul-Rahman in Zlatanova, 2008). Kot 3D-gradniki se omenjajo tetraedri, poliedri in poligoni. V navedenih delih avtorji ugotavljajo, da je 3D-grafične gradnike sicer mogoče shranjevati, saj SUPB podpirajo shranjevanje točk, linij in poligonov v 3D-prostoru, težave pa vidijo pri njihovem upravljanju, analizah, posredovanju in vizualizaciji. Navedene težave so izvirale iz dejstva, da takrat SUPB še niso podpirali podatkovnega tipa za prostorninske 3D-grafične gradnike in tako tudi niso omogočali upravljanja takšnih podatkov ter analiz v 3D-okolju.

3 *Angl. core cadastral domain model.*
4 *Angl. land administration domain model.*
5 *Sistem za upravljanje s podatkovnimi bazami.*

Med najpomembnejšimi vidiki upravljanja podatkov je preverjanje njihove skladnosti z njihovo formalno definicijo, kar velja tudi za 3D-prostorske podatke (Kazar *et al*., 2008; Ledoux, Verbree in Si, 2009). Slednje ima velik pomen tudi na področju 3D-katastrov (Karki, Thompson in McDougall, 2010). V navedeni raziskavi se avtorji niso omejili zgolj na notranjo pravilnost posameznih grafičnih gradnikov, ampak jih obravnavajo v kontekstu 3D-katastrskega sistema, kjer so pomembni medsebojni odnosi 3D-grafičnih gradnikov in odnosi do 2D-parcel.

Med ključnimi podatkovnimi komponentami katastra je poleg prostorskih razsežnosti tudi čas, ki ga lahko pojmujemo kot četrto razsežnost stvarnosti. Prve raziskave na tem področju (Oosterom *et al*., 2006) obravnavajo časovno problematične primere in se osredotočajo predvsem na pomen dodajanja časovne komponente v katastrski podatkovni model, ne glede na to, ali gre za 2D- ali 3D-kataster. Časovni vidik je obravnavan tudi v okviru takrat predlaganega standarda LADM (Döner *et al*., 2008) na primeru registracije podzemne infrastrukture v različnih državah. Avtorji vzpostavijo povezavo pravnega objekta in fizičnega objekta podzemne infrastrukture prek uporabe operacije območij (angl. *buffer*) in se hkrati oddaljijo od registracije geometrijskih podatkov o fizičnem objektu v katastru. Pomenljiva je teza avtorjev, da zemljiška administracija že od samega začetka upravlja tako s tremi prostorskimi kot tudi s časovno razsežnostjo v skladu s tehničnimi možnostmi, torej v obliki atributnih podatkov. Časovni del podatkovnega modela lahko temelji na registraciji stanj v času, ki se v osnovi uporablja v večini katastrskih sistemov, ali registraciji začetnega stanja in vseh nadaljnjih dogodkov.

3.1.3 Pravni vidik 3D-katastra

V prvem obdobju raziskav na področju 3D-katastra nepremičnin je bila pravna tematika zastopana šibkeje od informacijsko-tehnološko usmerjenih raziskav. Prva celovita in obširna raziskava pravnih vidikov 3D-katastra nepremičnin v širšem mednarodnem okolju prihaja iz Švedske (Paulsson, 2007), kjer se avtorica ukvarja z osnovnim problemom definicije 3D-nepremičninske enote (angl. *3D property unit*). Zaradi univerzalnosti jo opredeli kot prostorsko enoto, ki je horizontalno in vertikalno razmejena. Pravice, omejitve in odgovornosti, ki so tako razmejene v prostoru, razdeli na etažno lastnino in samostojna 3D-območja pravic. Etažna lastnina je obravnavana kot uveljavljen način urejanja pravic, ki so v prostoru horizontalno in vertikalno razmejene, zato je v navedenem delu obravnavana najpodrobneje. Avtorica podrobno in sistematično obravnava in primerja izbrane štiri pravne ureditve, ki imajo različno tradicijo in različne ureditve registracije pravic na nepremičninah: Nemčijo s tradicionalnim sistemom etažne lastnine in kodificiranim pravom, Švedsko s podobnim pravnim sistemom in novo zakonodajo, ki omogoča registracijo neodvisne 3D-nepremičninske enote, ter avstralski državi Novi Južni Wales in Viktorija, z običajnim pravom in zakonodajo, ki dovoljuje vzpostavitev tako etažne lastnine kot tudi neodvisne 3D-nepremičninske enote.

3.1.4 Organizacijski vidik – stanje in perspektive 3D-katastra

V mnogih objavah iz prvega desetletja intenzivnega raziskovanja na področju 3D-katatsrov nepremičnin je predstavljeno stanje in perspektive uvedbe 3D-katastra nepremičnin v posameznih državah. V večini so analizirani obstoječi katastrski sistemi s pravnega in tehničnega vidika, zapleteni primeri, kjer je treba registracijo nepremičnine urejati v treh razsežnostih, ter možnosti uvedbe 3D-katastra v posamezni državi. Med njimi najdemo tudi posamezne konceptualne zasnove, vsem pa je skupno, da obravnavane tehnične rešitve še niso neposredno izvedljive v praksi.

V Izraelu so raziskovali možnosti vzpostavitve 3D-katastra (Benhamu in Doytsher, 2003), kjer so rešitve iskali po načelu večnivojskega katastra, ki bi poleg podatkovnega sloja za tradicionalne parcele lahko vseboval tudi podatkovna sloja za objekte pod in nad površjem (Benhamu in Doytsher, 2001; Benhamu, 2006). Tehnične izzive, vezane na Izrael, pa tudi širše, sta predstavila Peres in Benhamu (2009), ko so se že okrepila prizadevanja za operativno[6] realizacijo 3D-katastra. Med državami velja izpostaviti še Kitajsko, kjer je zasebna lastnina lahko vzpostavljena le na grajenih strukturah. Tang in Yang (2009) sta razvila konceptualni model, ki bi omogočal registracijo 3D-nepremičninskih enot, a obenem priznavata, da takrat ni bil izvedljiv zaradi pomanjkanja podatkov ter neobstoječih informacijskih in tehnoloških rešitev za shranjevanje in upravljanje 3D-podatkov. V literaturi zasledimo tudi avstralske zvezne države Novi Južni Wales, Viktorija (Paulsson, 2007) in Queensland (Stoter, 2004) s tradicijo pravne ureditve in registracije 3D-nepremičninskih enot. Te so lahko formirane tudi za območja nad ali pod površjem Zemlje, neodvisno od fizičnih objektov. Sistem registracije nepremičnin z vidika shranjevanja podatkov o geometriji nepremičninske enote pa je v vseh navedenih zveznih državah v celoti temeljil na 2D-konceptih.

Norveška je v tem obdobju uveljavila zakonodajo, ki omogoča vzpostavitev samostojnih 3D-nepremičninskih enot (Valstad, 2010). Osnovne značilnosti te zakonodaje je obravnaval že Onsrud (2003). Registracija samostojnih 3D-nepremičninskih enot je mogoča le za namene registracije grajenih objektov (Valstad, 2006), podobno kot na Švedskem (Eriksson, 2005; Paulsson, 2007). V obeh državah katastrski sistem tehnično ni dovoljeval digitalne registracije 3D-geometrije nepremičninskih enot. Registracija posameznega stanovanja kot samostojne 3D-enote ni mogoča niti na Švedskem niti na Norveškem. Slednje je ostalo v domeni etažne lastnine. Poudariti velja, da imata obe državi enoten sistem zemljiške administracije, ki je pred leti nastal z združitvijo nekdanjega dualnega sistema (pravnega in tehničnega). Dejstvo izpostavljamo zaradi organizacijsko-institucionalnega vidika uvajanja 3D-katastra in drugih obsežnejših sprememb v zemljiško administracijo.

V nasprotju z navedenimi državami, ki so v obravnavanem obdobju pogosteje obravnavane zaradi njihovega načina urejanja in registracije 3D-nepremičninskih enot, je Nizozemska ohranjala tradicionalno ureditev katastrskega sistema. Država ima sicer že več desetletij enoten sistem zemljiške administracije znotraj ene organizacije (prej je imela tudi dualni sistem z delitvijo na zemljiški kataster in zemljiško knjigo). Pogosta pojavnost Nizozemske v raziskavah je predvsem posledica dejavnosti raziskovalcev ter sodelovanja akademske sfere z njihovo geodetsko upravo, kar je v začetku desetletja zelo pospešilo raziskave na področju 3D-katastrov (Stoter in Ploeger, 2003; Stoter in Salzmann, 2003; Stoter, 2004).

Slovenija je v prvem desetletju z uvedbo katastra stavb vzpostavila podlago za razvoj 3D-katastra (Pogorelčnik in Korošec, 2001; Rijavec, 2009), a vse do danes ni bilo intenzivnejšega razvoja v tej smeri,. Velika težava pri tem so slaba povezava zemljiških parcel in stavb, nedorečenost katastrskega evidentiranja infrastrukturnih objektov, ki niso stavbe, ter pomanjkljivi podatkovni model katastra stavb (glej tudi Drobež, 2016; Drobež *et al.*, 2017).

[6] *Z besedo 'operativno' v članku označujemo dejansko uporabo/izvedbo nečesa v katastrskem sistemu posamezne države.*

Glede operativne izvedbe 3D-katastra nepremičnin v praksi tudi ob koncu desetletja v literaturi večkrat zasledimo, da je potreben nadaljnji razvoj na vseh ustreznih področjih. Izstopa le pravno področje v tistih državah, kjer pravnih omejitev za registracijo 3D-nepremičninskih enot ni. Zanimivo je, da Çağdaş in Stubkjær (2009) v raziskavi, v kateri sta analizirala metodološke pristope doktorskih raziskav na področju razvoja katastrskih sistemov, ne izpostavljata 3D-katastra in navedenih doktorskih raziskav (Stoter, 2004; Paulsson, 2007) kot pomembnega dela razvoja sodobnih katastrov.

3.2 Raziskave na področju 3D-katastra po letu 2010

V letu 2011 je bila opravljena raziskava med člani FIG-ove delovne skupine o 3D-katastrih nepremičnin, v kateri je sodelovalo 36 držav članic navedene skupine (Oosterom *et al.*, 2011). Vsebina vprašalnika je bila osredotočena na inventarizacijo stanja po državah v letu 2010 in njihova pričakovanja za leto 2014. Rezultati zelo pomembno prispevajo k raziskavam o 3D-katastrih, saj omogočajo prost dostop do obširnega nabora podatkov o katastrskih sistemih številnih držav. Avtorji raziskave ugotavljajo, da imajo države različne katastrske sisteme, iz česar izhaja tudi neenotno pojmovanje 3D-katastra. Razlike so predvsem glede razumevanja povezave tradicionalne 2D-parcele in 3D-nepremičninskih enot s fizičnimi strukturami. Nobena od držav takrat še ni imela razvite možnosti shranjevanja in upravljanja 3D-podatkov o nepremičninskih enotah v katastrih. Glede načrtov in pričakovanj za leto 2014 je bila večina zelo zadržanih. Leta 2014 so predstavniki 31 držav podali odgovore na drugi, dopolnjen vprašalnik o stanju in pričakovanjih na področju 3D-katastra za leto 2018 (Oosterom, Stoter in Ploeger, 2014). V vseh državah, v katerih je pravni sistem omogočal registracijo 3D-nepremičninskih enot, so načini registracije, shranjevanja in upravljanja podatkov še vedno temeljili na 2D-zasnovanem katastru. Državam je bila skupna večinska »neskladnost« digitalnih katastrskih podatkovnih baz s shemo standarda ISO 19152:2012 (LADM, 2012). Glede shranjevanja 3D-podatkov v digitalni obliki močno izstopa Kitajska, ki v odgovorih na vprašalnik navaja, da njihova podatkovna baza omogoča shranjevanje, preverjanje in upravljanje 3D-geometrije nepremičninskih enot. A pri kitajskem primeru hkrati zasledimo izjemno majhno skupno število parcel glede na velikost države, zato gre sklepati, da opisano stanje velja le za omejena (urbana) območja Kitajske. Tudi kasnejše raziskave (Guo *et al.*, 2013; Ho *et al.*, 2013; Dimopoulou, Karki in Roič, 2016; Stoter *et al.*, 2017) potrjujejo, da Kitajska v začetku desetletja ni imela polno operativnega sistema 3D-katastra.

Leta 2011 je na Nizozemskem potekala druga delavnica o 3D-katastru, kar je bilo torej deset let po prvi. Zanimivo je, da je bila takrat napovedana naslednja, tretja delavnica v dveh ali treh letih, a je bila izvedena že v naslednjem letu, kar kaže na povečano zanimanje za raziskave in izmenjavo znanja na mednarodni ravni na tem področju. V poročilu o delavnici leta 2011 (Banut, 2011) je predstavljeno stanje na posameznih razvojnih področjih 3D-katastra, ki so deljena na pravne vidike, prve registracije 3D-nepremičninskih enot, upravljanje 3D-prosotrskih podatkov in vizualizacijo, posredovanje in dostopnost podatkov o 3D-nepremičninskih enotah:

- Na pravnem področju je izpostavljena težava neusklajenosti terminologije ter različnih opredelitev 3D-katastra.
- Več kot dve tretjini prispevkov opisujeta sisteme zemljiške administracije posameznih držav in načine urejanja višinske delitve nepremičninskih enot v luči aktualnih raziskav in podatkovnih modelov.
- Na področju upravljanja digitalnih 3D-prostorskih podatkov, predvsem področja analiz in izvajanja

operacij v SUPB in GIS[7], je prepoznan močan zaostanek za področjem 3D-vizualizacije prostorskih podatkov, ki je v prvem desetletju tega tisočletja močno napredovalo. Izpostavljena je pomembnost spletne dostopnosti 3D-podatkov katastrov nepremičnin in tehnik 3D-vizualizacije na spletu.

Tematski poudarek tretje delavnice leta 2012 je bil na razvoju in dobrih praksah na področju 3D-katastra (Oosterom, 2012). Izražena je bila predvsem potreba po večjem številu raziskav in primerjalnih analiz pravnih ureditev v različnih državah in zahteva po uporabi obstoječih standardov, tako s področja modeliranja nepremičninskih enot (LADM) kot tudi s področja modeliranja fizičnih prostorskih struktur v informacijskih sistemih zemljiške administracije. Med drugim je bil poudarjen pomen vizualizacije 3D-nepremičninskih objektov, saj so potrebe in izzivi drugačni kot pri vizualizaciji bolj razširjenih 3D-modelov mest in pokrajin.

Izhajajoč iz prispevkov z delavnic in konferenc združenja FIG leta 2011 in 2012, Oosterom (2013) podaja oris razvoja na področju 3D-katastrov, kjer predstavi tudi najpomembnejše teme za prihodnje raziskave. Izpostavljamo predvsem tematike, ki so še vedno aktualne na mednarodni ravni:

– Že navedeno pomanjkanje raziskav na pravnem področju sta Paulsson in Paasch (2013) utemeljila na podlagi študije 156 objav angleških člankov med letoma 2001 in 2011. Ugotovila sta pomanjkanje predvsem terminoloških in primerjalnih raziskav, ki bi zajemale več držav in pravnih ureditev na področju 3D-katastra.
– Višine in višinske sisteme 3D-katastrov sta prvič izčrpneje obravnavala Navratil in Unger (2013). Predstavila sta splošno problematiko višinskih referenčnih sistemov in omejitve ter zahteve 3D-katastrov, tudi na primerih iz prakse. Največ pozornosti je namenjene analizi prednosti in slabosti uporabe absolutnih in relativnih višin v 3D-katastru.
– Zelo pomemben element, ki ima velik vpliv na dinamiko uveljavitve 3D-katastra, je razmerje med stroški in koristmi, ki jih prinaša. Ena od redkih takšnih raziskav na primeru Trinidada in Tobaga ugotavlja pozitivno razmerje stroškov in koristi na urbanih in gosto poseljenih območjih ter nahajališčih naravnih surovin (Griffith-Charles in Sutherland, 2013). Avtorja ugotavljata, da je smiselno proučiti možnosti vpeljave 3D-katastra le na nekaterih območjih, kjer koristi odtehtajo stroške.
– Operativna uvedba 3D-katastra med drugim zahteva določitev jasnih pravil glede razmejitev prostora na 3D-nepremičninske enote ter modeliranja teh enot v 3D-okolju, skupaj s postopki preverjanja njihove skladnosti s postavljenimi pravili. Slednje je v treh prostorskih razsežnostih veliko težavnejše, saj je nabor pravil obširnejši, pa tudi postopki preverjanja skladnosti z njimi so zahtevnejši kot v tradicionalnem 2D-katastru. Karki, Thompson in McDougall (2013) so navedeno področje podrobno proučili, oblikovali nekatere rešitve ter nabor izzivov in nerešenih vprašanj. Avtorji sklenejo, da razvoj sistemov zemljiške administracije v smeri 3D-katastra ni mogoč v kratkem časovnem obdobju. Ena od rešitev je postopno prilagajanje obstoječih sistemov, kar zagovarjajo Guo *et al*. (2013). Avtorji na primeru kitajskega katastra izhajajo iz obstoječega pravnega sistema in 2D-podatkovnega modela, v katerega vključijo elemente 3D-katastra. Članek je zanimiv tudi za primerjavo z rezultati že navedene raziskave o razvoju 3D-katastra (Oosterom, Stoter in Ploeger, 2014), kjer bi lahko za Kitajsko napačno sklepali, da je že pred letom 2014 imela polno delujoč sistem 3D-katastra.
– Primerjava katastrskih sistemov med posameznimi državami je zaradi njihove različnosti zelo težavna. Pouliot, Vasseur in Boubehrezh (2013) so primerjali modele katastrskih sistemov Francije

[7] *Geografski informacijski sistem.*

in Kanade, s poudarkom na tretji prostorski razsežnosti, na podlagi standarda LADM (2012). Kot najzahtevnejši del izpostavijo transformacijo podatkovnega modela posameznega sistema v standardno shemo LADM, kar v nadaljevanju omogoča neposredno medsebojno primerjavo katastrskih sistemov, njihovih razredov in atributov. Predlagajo in utemeljijo tudi vključitev prostorninske geometrije v standard, s čimer bi povečali uporabnost standarda LADM tudi na področju 3D-katastra.

Prispevki četrte delavnice združenja FIG na temo 3D-katastra iz leta 2014 so vsebinsko večinoma tehnično usmerjeni, ne glede na pozive o pomanjkanju obravnave pravne problematike (Paulsson in Paasch, 2013):

- Pravni vidik je kot glavna tematika na delavnici obravnavan le v eni objavi v obliki nacionalne študije za Poljsko (Karabin, 2014).
- Izrazito se je povečala obravnava ISO-standarda LADM (2012) in odprtega standarda CityGML združenja OGC[8] (CityGML, 2012), ki ju v kombinaciji ali samostojno zasledimo v osmih objavah. Število raziskav in predstavitev sistemov po posameznih državah je glede na prejšnje delavnice upadlo. Med objavami sta zanimivi dve (Almeida *et al.*, 2014; El-mekawy, Paasch in Paulsson, 2014), ki med prvimi obravnavata področje prostovoljnega zbiranja prostorskih podatkov in povezavo informacijskega modeliranja stavb (BIM[9]) s 3D-katastrom. Izpostavljeni tematiki sta predstavljeni kot izziv za 3D-kataster, saj sta obe področji danes raziskovalno zelo intenzivni na širšem področju geo-znanosti. BIM predstavlja potencial za razvoj večnamenskega 3D-katastra in pomembno področje prihodnjih raziskav (Rajabifard, 2014).
- Vsebina objav kaže na večje zanimanje za raziskave na področju 3D-vizualizacije (Navratil in Fogliaroni, 2014; Pouliot, Wang in Hubert, 2014; Ribeiro, de Almeida in Ellul, 2014), kar potrjujeta tudi obsežni doktorski disertaciji iz tega obdobja (Shojaei, 2014; Wang, 2015). Wang (2015) se je osredotočil na ocenjevanje primernosti načinov vizualizacije 3D-modelov za primer prikaza etažne lastnine, med tem ko se je Shoaei (2014) ukvarjal predvsem z analizami uporabniških zahtev in njihovih potreb.

3.2.1 Izzivi na področju 3D-katastra s pravnega vidika

Kljub relativno skromni obravnavi pravnega vidika 3D-katastra na navedeni FIG-ovi delavnici leta 2014 je področje bilo in je še vedno aktualno na mednarodni ravni. Na področju zemljiške administracije in nepremičninskih evidenc se namreč srečujeta koncepta fizičnega prostora in abstraktnega prostora, kjer se na »abstraktne« prostorske enote nanašajo pravice, omejitve in odgovornosti. Ob nepopolnem poznavanju področja ju lahko enačijo na podlagi pogostega sovpadanja meja fizičnih struktur in meja pravic oziroma omejitev. Razdelitev prostora s pravnega vidika je v osnovi abstraktna, njena povezava s fizičnim prostorom pa je vzpostavljena v različnih oblikah in iz različnih vzrokov, razlikuje pa se med pravnimi sistemi. Področje 3D-katastra je pogosto usmerjeno v obravnavo razdelitve stavb na nepremičninske enote, kjer gre za povezavo med prostorom pravnega pomena in fizičnim prostorom ter njegovimi strukturami (Aien, 2013; Aien *et al.*, 2013, 2015), iz česar izhaja tudi pogosto enačenje fizičnih meja prostora s pravnimi (abstraktnimi). V navedenih raziskavah so avtorji razvili model 3DCDM[10], ki združuje fizične in pravne vidike razdelitve prostora za potrebe 3D-katastra.

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[8] Open Geospatial Consortium: http://www.opengeospatial.org/.
[9] Angl. building information modelling.
[10] Angl. 3D-cadastral domain model.

Razvoj področja 3D-katastra v prvem desetletju je privedel do razhajanj glede pravnih opredelitev nepremičnine v treh razsežnostih (Paasch in Paulsson, 2012). Avtorja ugotavljata, da slednje povzroča težave tudi na raziskovalnem področju, saj so zaradi neenotnih opredelitev temeljnih pojmov omejene možnosti primerjalnih analiz in študij. Kot poudarita, mora biti pravna opredelitev nepremičnine v treh razsežnostih dovolj široka, da je lahko sprejemljiva v večini pravnih sistemov. Poleg tega mora opredelitev takšno nepremičnino jasno in enolično opredeliti ter jo razmejiti od tradicionalne nepremičnine v dveh razsežnostih. Avtorja predlagata univerzalno opredelitev 3D-nepremičnine, kot jo je že predlagana Paulssonova (2007). Z vidika pravno usmerjenih raziskav je zanimiva raziskava Ho *et al*. (2013), kjer avtorji izhajajo iz teze, da je tehnologija dovolj razvita, pa tudi pravni sistemi v številnih državah dovoljujejo registracijo 3D-nepremičninskih enot, zato mora obstajati zaviralna sila, ki preprečuje hitrejše uveljavljanje 3D-katastra. To silo avtorji pojasnijo in razčlenijo z institucionalno teorijo in utemeljijo, da so razlogi za počasne spremembe v počasnem prilagajanju odgovornih organizacij in močno uveljavljenem 2D-konceptu v sistemih zemljiške administracije. Oosterom in Lemmen (2015) izpostavita 3D- (in 4D-) administracijo kot enega od pomembnejših razvojnih trendov zemljiške administracije in s tem tudi standarda LADM. Predstavita raziskave, ki izhajajo iz prve tematske delavnice po objavi standarda LADM, med katerimi sta tudi dve na temo razvoja 3D-katastra v Koreji in Maleziji (Lee *et al*., 2015; Zulkifli *et al*., 2015).

3.2.2 Izzivi pri uveljavljanju 3D-katastra

Posebno poglavje v razvoju 3D-katastra je njegova operativna uvedba. Prve raziskave na to tematiko so potekale v okviru nizozemskega projekta, namenjenega podpori prehoda na 3D-kataster, ki temelji na dveh izvedbenih fazah (Stoter, Oosterom in Ploeger, 2012; Stoter, Ploeger in Oosterom, 2013). Prva faza je bila namenjana pridobivanju izkušenj in se v rešitvah prilagaja obstoječim pravnim in tehničnim okvirom. Njen izvedbeni del se nanaša na možnosti registracije nepremičnine na podlagi dokumenta v obliki zapisa PDF, ki vsebuje 3D-geometrijo in je povezan z drugimi podatki o nepremičnini prek povezave v podatkovni bazi. Zanimiva je ocena stroškov registracije in vzdrževanja sistema, ki naj za nove stavbe ne bi bili višji od obstoječih stroškov registracije. Prva faza uvedbe 3D-katastra danes omogoča reševanje nekaterih kompleksnih situacij, predvsem z vidika nedvoumnega prikaza razdelitve na nepremičninske enote, še vedno pa obstoječ 2D-sistem zemljiške administracije v osnovi ostaja nespremenjen. Druga faza je zasnovana veliko ambiciozneje, saj predvideva uvedbo 3D-katastra, ki omogoča celovito digitalno registracijo nepremičninskih enot, vključno z geometrijo, v obliki 3D-objekotv (prostorninskih teles) neposredno v podatkovni bazi katastra. V zvezi z drugo fazo je nerešenih veliko vprašanj glede kontrole geometrije, zahtevane položajne in geometrijske natančnosti, podatkovnih formatov, vključitve ukrivljenih ploskev, delno odprtih gradnikov ipd. (Stoter *et al*., 2017).

V Rusiji so začeli projekt 3D-katastrskega modeliranja v sodelovanju z nizozemskimi raziskovalci. Razvili so prototip, ki se osredotoča predvsem na način modeliranja in prikazovanja 3D-nepremičninskih enot. V načrtih so opredelili pilotni projekt na manjšem območju, kjer bi se približali realni izvedbi registracije. Vandysheva *et al*. (2012) poudarjajo pomen samodejne kontrole ob vpisu novih nepremičninskih enot v smislu skladnosti s predhodno postavljenimi pravili. Kljub intenzivnim naporom za vzpostavitev 3D-katastra in modernizaciji sistema zemljiške administracije v zadnjih letih, ta v Rusiji še vedno temelji na dveh prostorskih razsežnostih (Ilyushina, Noszczyk in Hernik, 2017).

3.3 Aktualne teme in raziskave na področju 3D-katastra

Zadnja delavnica na področju 3D-katastra pod okriljem FIG-a je potekala leta 2016. Da je področje raziskovalno aktivno, med drugim kaže povečano število prispevkov (31) glede na predhodno delavnico (25). Izbrani prispevki so v razširjeni različici zbrani tudi v posebni izdaji mednarodne revije *ISPRS International Journal of Geo-Information* z naslovom R*esearch and Development Progress in 3D Cadastral Systems 2017*.

Najbolj opazno je ponovno veliko število objav, vezanih na analizo stanja v posameznih državah in različnih možnosti za razvoj sistemov zemljiške administracije, med katerimi prevladujejo objave, ki se osredotočajo na tehnične rešitve modeliranja 3D-neprmičninskih enot v informacijskih sistemih zemljiške administracije (Araújo in Oliveira, 2016; Dimas, 2016; Soon, Tan in Khoo, 2016; Gulliver, Haanen in Goodin, 2017). Na to področje se nanašajo tudi druge objave v mednarodno odmevnih revijah. Tako Aien *et al.* (2017) izpostavijo šest najbolj uveljavljenih podatkovnih modelov v katastru, kjer je so se zaradi različnosti sistemov zemljiške administracije pojavili številni podatkovni modeli. Med njimi avtorji izpostavljajo tri (LADM, ePlan, ArcGIS Parcel Data Model) in jih podrobneje analizirajo z vidika uporabnosti za 3D-kataster. Podatkovni model 3DCDM, ki ga je v okviru doktorske raziskave razvil vodilni avtor, v raziskavi ni vključen, niti ni v njej omenjen. Avtorji ugotavljajo, da nekateri obravnavani podatkovni modeli omogočajo modeliranje 3D-nepremičninskih enot, a pri vsakem razkrijejo pomembne omejitve za razvoj 3D-katastra.

Na raziskovalni ravni je spet močneje zastopano pravno področje raziskav (Kitsakis in Dimopoulou, 2017; Vučić *et al.*, 2017), na čelu z obširno primerjalno študijo med izbranimi državami (Kitsakis, Paasch in Paulsson, 2016; Paasch *et al.*, 2016). Kitsakis, Paasch in Paulsson (2016) predstavijo pravno opredelitev 3D-nepremičninskih enot v različnih državah (Avstrija, Brazilija, Hrvaška, Grčija, Poljska in Švedska) in načrte za prihodnji razvoj. Švedska, kot edina od naštetih držav, v pravnem sistemu ne omejuje registracije 3D-nepremičninskih enot, a upravljanje podatkov, tako kot v drugih državah, tudi na Švedskem še vedno temelji na 2D-konceptih.

Na področju modeliranja in upravljanja podatkov v 3D-katastrih je zanimiva raziskava Janečka in Součka (2017). Avtorja predstavljata aktualno stanje na širšem področju 3D-geoinformatike, ki zajema koncepte, podatkovne modele, standarde in operacije, povezane s 3D-prostorskimi podatki. Poudarek je na trenutnih zmogljivostih prostorskih podatkovnih baz z vidika modeliranja in upravljanja 3D-prostorskih podatkov. Izredno aktualna tema je povezava oziroma vključevanje podatkov BIM v podatkovni model 3D-katastra. Vse več raziskav se v povezavi s podatki BIM usmerja tudi na modeliranje notranjosti stavb za potrebe registracije nepremičninskih enot (Oldfield *et al.*, 2016; Atazadeh, 2017). Atazadeh *et al.* (2017) obravnavajo BIM kot osnovo za upravljanje pravic in omejitev na stavbah. Predlagajo razširitev podatkovnega modela tako, da bi ta podpiral tudi vnos podatkov o pravicah in omejitvah v stavbah in njihovo upravljanje. Med drugim se avtorji dotikajo aktualnega vprašanja odnosa 3D-enot pravnega pomena in fizičnega modela stavbe. Poleg prednosti avtorji navajajo omejitve predlaganega pristopa, ki vključujejo institucionalne ovire, preobširno podatkovno strukturo ter problem neusklajenosti med načrtovanim in dejansko zgrajenim objektom.

V modeliranje notranjosti stavb je usmerjeno raziskovalno delo Zlatanove *et al.* (2016), kjer je prvič v okviru raziskav na področju 3D-katastra uporabljen v letu 2014 sprejet standard OGC – IndoorGML

(2014). V prispevku avtorji obravnavajo možnosti za povezavo navedenega standarda s standardom LADM. Razširjene raziskave v tej smeri predstavlja Alattas *et al.* (2017). Standard IndoorGML temelji na večslojnem prostorsko-dogodkovnem modelu, prvotno namenjenem podpori navigaciji v notranjosti stavb, predlaganem v letu 2009 (Becker, Nagel in Kolbe, 2009). Navedena skupina avtorjev je bila vodilna tudi pri razvoju starejšega standarda za modeliranje mest in pokrajin v 3D-okolju CityGML. Standard IndoorGML uvaja celični pristop modeliranja notranjosti stavb, ki je po načelu dualnosti (Munkres, 1984) povezan z matematičnim grafom. Ta omogoča izvajanje algoritmov iskanja optimalnih poti v podporo navigaciji, pa tudi drugih algoritmov, ki temeljijo na topoloških odnosih med grafičnimi gradniki. Standard omogoča razširitve podatkovnega modela v obliki razširitvenih modulov za različna področja. Kang in Li (2017) sta posebej izpostavila možnost realizacije razširitvenega modula standarda IndoorGML za področje 3D-katastra. Povezovanje modelov mest in modelov notranjosti stavb ter podzemnih objektov je prepoznan raziskovalni problem tudi v skupini strokovnjakov za področje globalnih prostorskih informacij pri Združenih narodih UN-GGIM (2015).

4 SKLEP

Začetki uveljavljanja termina 3D-kataster segajo v čas nastanka dokumenta *Cadastre 2014* (Kaufmann in Steudtler, 1998). Za opredmetenje zapisanih ciljev je bila leta 2001 izvedena prva delavnica pod okriljem FIG, ki je spodbudila raziskave na področju 3D-katastra. Jasneje so se določili različni vidiki razvoja 3D-katastrov: pravni, tehnični in administrativni, od katerih sta prva dva v raziskavah močneje zastopana. Za prvo desetletje je značilno veliko število analiz sistemov zemljiške administracije v posameznih državah in predlogi za njihovo nadgradnjo. Skupne ugotovitve so bile, da je za vzpostavitev 3D-registracije potreben dodaten razvoj na vseh navedenih področjih raziskovanja.

Na tehničnem področju raziskovanja 3D-katastrov je velik pečat pustila doktorska disertacija Stoterjeve (2004). Večina raziskav, ki sledijo, se namreč navezuje na njene izsledke, opredelitve in predloge. Na pravnem področju izstopata Švedska, ki je leta 2004 v svoj pravni sistem uvedla možnost registracije 3D-nepremičninske enote, in Avstralija z dolgo tradicijo možnosti registracije samostojnih 3D-nepremičninskih enot. Med najodmevnejšimi študijami stanja pravnih sistemov na področju 3D-katastra je doktorska disertacija Paulssonove (Paulsson, 2007), ki podaja celovit pregled in uvid v pravni vidik 3D-katastra. Dokument *Cadastre 2014* je sprožil tudi začetne zasnove podatkovnega modela CCDM katerega namen je poenotenje ključnih sestavin sistemov zemljiške administracije po svetu. Gre za neposrednega predhodnika mednarodnega standarda LADM (2012), ki v osnovi ne omejuje evolucije tradicionalnega 2D-katastra v 3D-kataster.

Zadnje desetletje raziskav na področju 3D-katastra zaznamuje predvsem objava standardov LADM (2012) in CityGML (2012) ter tudi IndoorGML (2014). V večini raziskav v tem obdobju se proučujejo možnosti uporabe navedenih standardov, analizirajo prednosti in slabosti posameznih standardov ter se medsebojno primerjajo. Manj raziskav se nanaša na pravni vidik, kar ugotavljata že Paulsson in Pasch (2013). Nizozemski raziskovalci so v tem obdobju pomembno prispevali k uvajanju konceptov 3D-katastra v prakso. Ko se bo za razvoj katastra v smeri podpore tretji razsežnosti odločilo več držav, se bodo okrepile tudi raziskave. Raziskovalni izzivi na področju 3D-katastra se nadalje nanašajo na integracijo podatkov iz drugih domen, predvsem so pri tem aktualne raziskave glede uporabe oziroma vključevanja podatkov BIM v podatkovni model 3D-katastra in nasprotno. Dodatno je aktualna obravnava oziroma modeliranje notranje strukture stavb, ki je zahtevna tako z vidika strukture podatkov in kompleksnosti podatkovnih modelov kot tudi z vidika pridobivanja podatkov in integracije modelov notranjosti stavb in zunanjih modelov mest ter pokrajin (UN-GGIM, 2015).

Zahvala

Pregledni članek je rezultat raziskovalnega dela v okviru raziskovalnega programa št. P2-0227 z naslovom *Geoinformacijska infrastruktura in trajnostni prostorski razvoj Slovenije*, ki ga sofinancira Javna agencija za raziskovalno dejavnost Republike Slovenije (ARRS) iz državnega proračuna.

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PRILOGA B

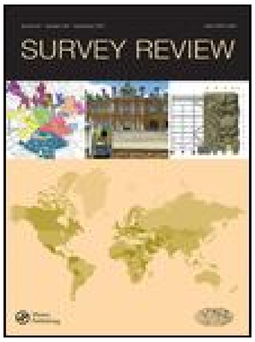
Indoor space as the basis for modelling of buildings in a 3D Cadastre

Tekavec, J., Čeh, M., Lisec, A. (2020)

Survey Review

DOI: 10.1080/00396265.2020.1838761

Faktor vpliva za leto 2019: 1,660 (Q3)



Taylor & Francis
Taylor & Francis Group

Survey Review

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ysre20

Indoor space as the basis for modelling of buildings in a 3D Cadastre

Jernej Tekavec , Marjan Čeh & Anka Lisec

Indoor space as the basis for modelling of buildings in a 3D Cadastre

Jernej Tekavec *, Marjan Čeh and Anka Lisec

This paper presents a 3D cadastral data model for buildings. A review of the relevant research shows that a common concept in the 3D cadastre domain is using the legal building unit, i.e. real property unit, as the core modelling unit. Alternatively, this study proposes using indoor space as a core modelling unit. The main reason is to enable the efficient integration of cadastral data with the data from other domains. On the conceptual level, the model is linked to the Land Administration Domain Model (LADM). The integration options are studied for three international standards: IFC, CityGML and IndoorGML.

Keywords: 3D cadastre, indoor space, integration, BIM, CityGML, IndoorGML

Introduction

Within a cadastral system, i.e. a land administration system, a large volume of relatively detailed, well-structured and high-quality geospatial data are stored and managed that have applications beyond the land administration domain, e.g. in forestry, agriculture, and spatial planning. In the last two decades, the tendency towards the inclusion of a vertical dimension in cadastral systems has been evident in many countries worldwide and is generally characterised by the term '3D Cadastre' (FIG 3D cadastres 2019). An upgrade of a traditional 2D cadastral data model to 3D can make the stored data more useful for new and existing applications in many (also new) domains that are related to land administration. One of the options to achieve this is to design the 3D cadastral data model to allow cross-domain integration.

In the context of this study, the term cadastral data refers to the data that specifies the spatial extent of real property units, which are a subject for the registration of rights, restrictions and responsibilities (RRR). Although cadastral data modelling is closely related to the legal framework and initial real property registration, we address the 3D cadastral modelling of real property units concerning the object's physical characteristics in this work. The approach is not a novelty in the cadastre domain. Various aspects of 3D cadastral data modelling are summarised and discussed in van Oosterom *et al.* (2018). Among the others, the authors state that in most cases, like in 2D cadastre, the ownership of a 3D parcel implies the ownership of all physical objects that are located within the defined space. From this perspective, 3D data on physical space can be used to describe physical reality in cadastre, which should be related to the 'legal reality' (van Oosterom *et al.* 2018).

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Modelling of buildings and its features represents one of the main driving forces for the introduction of 3D spatial data, not only in the land administration domain, but also in city and landscape modelling, and AEC. Every listed domain has its particularities in terms of requirements, constraints, rules and solutions. Consequently, the data on buildings from different domains can vary a lot in many aspects – not only in data format but also in quality, detailedness and completeness, semantics and object definitions. These challenging gaps between building data models are the basis for many current research activities attempting to link or integrate the 3D Building Information Modelling data, i.e. BIM data, and 3D geospatial data from Geographic Information Systems, i.e. GIS data. Deng *et al.* (2016) propose an instance-based method for mapping between CityGML (OGC 2012) and Industry Foundation Classes (IFC) (ISO 2018) schemas. Liu *et al.* (2017) provide a state-of-the-art review of GIS-BIM integration methods. Ohori *et al.* (2018) present practical results of GIS-BIM integration project. The cadastral systems can significantly benefit from cross-domain data integration capability. The first gain is the provision of high-quality AEC data, i.e. BIM, as input data for real property unit formation within a land administration system, and the second is the increased potential for linking and integrating cadastral data with other data sources to improve existing and to design new geospatial applications.

The main aim of this study is to develop a cadastral data modelling approach for buildings that uses indoor space as the core modelling object instead of a building part or real property unit. This idea is communicated through the design and implementation of a 3D cadastral data model. We address all types of buildings, where the division of real property is relevant (e.g. residential, commercial, industrial and their combinations). Apart from providing the reference, the paper does not investigate the concepts of 3D modelling of non-physical legal spaces (e.g. legal spaces not related to buildings). It has to be emphasised that various cadastral systems have been

Received 27 March 2020; accepted 14 October 2020
DOI 10.1080/00396265.2020.1838761

developed worldwide, with different origins and purposes. The main aim of our study has been to provide a concept for 3D cadastral building modelling based on the physical characteristics of buildings. For its implementation, a relation to the legal space has to be defined in a selected jurisdiction, but this is beyond this study. Although the building's indoor spaces as physical features may not be relevant for managing all RRRs, they can be used to integrate cadastral data with the data from other domains.

In the next section, we present a synthesis of the research related to the data models that allow the realisation of a 3D cadastre and we identify their key relevant features. In the following section, we design a conceptual 3D cadastral model, which we link to the standardised Land Administration Domain Model (LADM) (ISO 2012). this is followed by the implementation in a spatial DBMS (Database Management System). Based on the data model, we investigate the integration capabilities with data that corresponds to IFC, the CityGML standard and IndoorGML standard (OGC 2014).

3D cadastral data models

The term 3D cadastre is relatively broad and incorporates technical, legal and organisational aspects of 3D cadastral systems. At the international level, the research concerning all those aspects is concentrated mainly under the FIG working group on 3D cadastres. During the last two decades of intensive research, significant progress has been achieved in all the aspects, resulting in the recent comprehensive FIG publication (van Oosterom 2018) that also presents the data models related to a 3D cadastre with an emphasis on the LADM standard data model.

LADM is designed to provide a comprehensive data model for land administration. It provides an international framework for the cadastral data modelling but does not prescribe the modelling approach and technical data formats. Its core consists of linked packages related to parties, RRR, basic administrative units and spatial units. These packages represent the core of a land administration system. Lemmen *et al*. (2015) emphasise that LADM is designed to represent legal space and enables 3D representation. Registration of physical spaces is beyond the scope but, as the authors argue, investigation of LADM should be related to other geo-information standards (CityGML, LandXML, IFC).

The absence of physical space representation in LADM gave rise to research activities studying the relationship between physical and legal space in the context of 3D real property registration (Paasch *et al*. 2016, Larsson *et al*. 2020) as well as various ways of physical data modelling and visualisation to source legal spaces for 3D cadastres (Shojaei 2014), especially for buildings. The LADM forthcoming revision is strongly considering linking physical and legal objects, linking outdoor and indoor models, and is promoting the integration with several encodings (BIM/IFC, GML, CityGML, LandXML, IndoorGML etc.) (van Oosterom *et al*. 2019). El-Mekawy and Ostman (2012) argued that neither of the existing models allowed modelling of a 3D cadastral system and proposed an extension of the Unified Building Model (El-Mekawy 2010) to make it feasible for application in 3D cadastral systems. The 3D cadastral data model (3DCDM) developed by Aien (2013) was intended to address the complex relations of legal and physical space. The model enables efficient modelling of complex situations, especially in the built environment. It provides various types of both legal and physical objects and their geometric representations. Although the model solved virtually all possible complex situations, Aien *et al*. (2015) acknowledged its limitations, especially in the integration and implementation aspects. Knoth *et al*. (2018) aimed to design a building model by the identification of common elements among the selected building models. By extending the core model, the authors provided a feasible model for a 3D cadastre that integrated physical and legal aspects of a building. Li *et al*. (2016) studied the integration of CityGML and LADM with a focus on condominium units in buildings based on the application domain extension (ADE) for CityGML, which was also proposed by Góźdź *et al*. (2014) and Rönsdorf *et al*. (2014). The common feature of all presented the 3D cadastral data models is the existence of a legal building unit, i.e. real property unit, that represents a core modelling object for a 3D cadastre, either by explicit modelling in the model or linking to LADM classes representing the legal units.

Recently, Rajabifard *et al*. (2018) identified the relevant spatial information models and evaluated their ability to model legal interests and boundaries in Victoria, Australia, with a focus on the built environment. The authors classify the cadastral data models to legal, physical and integrated ones that combine legal and physical aspects in one model. They have emphasised the need for further research if indoor spaces are used to define the geometry of legal spaces within a 3D cadastre. The topic is especially challenging with respect to, among others, the multi-purpose cadastre and spatial analytics, for instance in relation to indoor navigation as proposed by Alattas *et al*. (2020) and Tekavec and Lisec (2020). This study aims to address this need and contribute to the development and implementation of the idea of linking physical indoor spaces with legal spaces in the context of a 3D cadastre.

Materials and methods

The 3D cadastral data model presented in this section is based on the result of the synthesis of the cadastral data models and considering the data model design objectives as presented below. As an alternative to other 3D cadastral data models, we focus on a building's indoor space as the core spatial unit. In this study, we define indoor space as the space that is bounded by the inward-facing three-dimensional surfaces (interior surfaces) of walls, floors, ceilings and other structural parts of the building. These spaces can be represented by 3D volumetric geometries, i.e. solids. At the passages between two indoor spaces, the solid geometries touch each other (Fig. 1) aiming to integrate topologic relations between neighbouring spatial units.

The boundaries of a real property unit (legal abstraction of the space) in the buildings may differ between jurisdictions, where we should distinguish, for example, the definition of a legal boundary which can coincide with the inward-facing or outward-facing surfaces of walls, floors, ceilings, and other structural parts of the building, or it might be defined in the middle of the wall, etc. (see also Cemellini *et al*. 2020). However, the possession or occupation of the physical space in a building is mainly related to indoor space. This makes it logical to focus on indoor spaces as core spatial units when modelling a

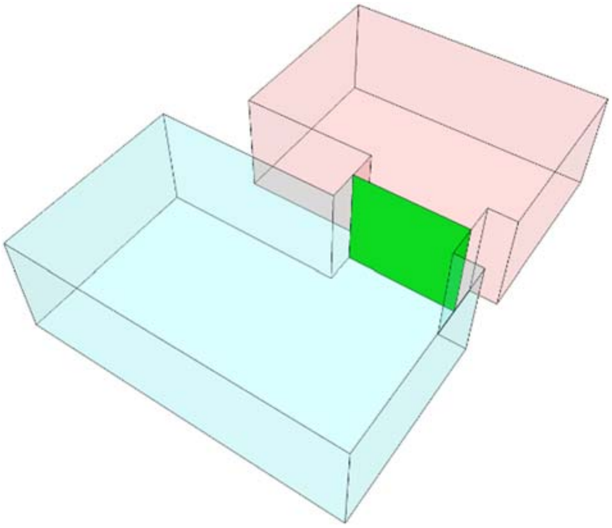

Figure 1 The passages between indoor spaces are realised by touching surfaces (green)

building for RRR registration. Therefore, we define the real property unit as a group of indoor spaces (Fig. 2). The model is built on the presumption that for buildings, the indoor space represents a key object of interest for cadastral systems. The extension of these 'basic spatial units' can be applied in the sense of adding 'wall solids' (the whole width, half of the width, etc.).

In addition to being a feasible solution for the definition and geometric representation of a legal situation in the building, the indoor space also represents the most integrative object for cross-domain integration of building information with 3D cadastral data (Knoth *et al*. 2018).

Data model design

The development of the proposed cadastral data model has been guided by the objectives, identified by the authors, that are presented below. We believe that fulfilling these objectives is among the most important prerequisites to ensure an efficient system for 3D cadastral

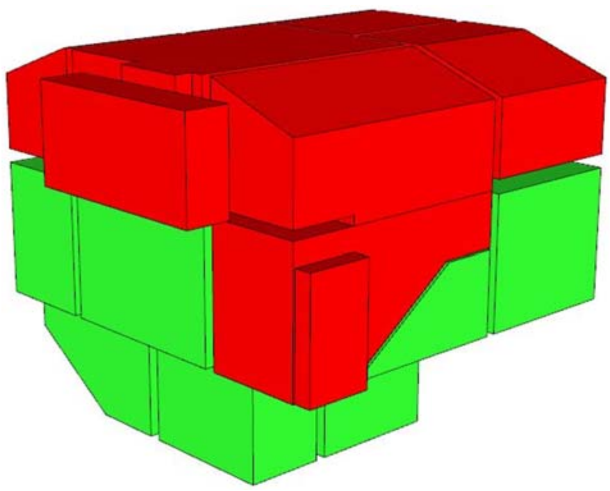

Figure 2 Two real property units (red and green) represented by groups of spatially linked indoor spaces

registration of buildings that is compatible with traditional 2D parcel-based cadastral systems.

(1) The cadastral data model for buildings should not require storage and maintenance of the data outside the cadastral domain.

(2) The cadastral data model should provide data that is structured in a way that enables as wide a cross-domain integration as possible on the data input and output sides.

(3) The cadastral data model should differentiate building data from land parcel data (e.g. for buildings, it should provide a separate (but integrated) data model or separate object classes) aiming to provide a step-by-step development of a 3D cadastre within a traditional 2D data model.

(4) The implementation should be feasible in a database management system (DBMS).

The first objective can be perceived as contradictory to our decision to focus on indoor spaces, but as it is stated in the justification for this decision, indoor spaces represent the main spatial units to which RRRs are related and provide less ambiguity in the representation of a legal situation in a building. However, following the first objective is challenging, as what belongs in the cadastral domain depends on the jurisdiction. Lemmen *et al.* (2015) provide a list of fields related to but outside LADM, according to which physical registration of buildings is out of the LADM (cadastral) domain. On the other hand, much research shows that a very strong relationship exists between physical and legal space in the built environment (Aien *et al*. 2015, Li *et al*. 2016, Knoth *et al*. 2018). Larsson *et al*. (2020) study the conversion of 2D analogue cadastral boundary plans into 3D digital information and discuss the integration with BIM. Rajabifard *et al*. (2019) suggest that cadastral systems cannot and should not ignore the physical space, especially considering the second objective, which emphasises the multi-purpose role of the cadastre. The terms 'physical space' and 'physical boundary' used in this study refer to the real world and its physical features, while 'legal space' and 'legal boundary' refer to abstract space and its features that have legal meaning. There seem to be two options for cadastral systems regarding consideration of physical space.

(1) Consider legal space in the cadastral model, as suggested by LADM (Lemmen *et al.* 2015): this way the first objective is fully met, but on the other hand, we lose the connection to physical space, which is crucial to have cross-domain data integration capabilities that constitute the essence of the second objective.

(2) Use an integrative approach, based on several recent studies (Aien *et al.* 2015, Atazadeh *et al.* 2017, Oldfield *et al.* 2017, Thompson *et al.* 2017, Knoth *et al.* 2018, Atazadeh *et al.* 2019, Sun *et al.* 2019) following the second objective and make a trade-off by storing and maintaining data out of the cadastral domain.

However, there is a third, alternative approach, as proposed and used by this study. Instead of using one of the approaches presented above, we constrain the legal spaces with physical boundaries, giving them physical characteristics. More precisely, we constrain the boundaries of legal spaces (i.e. legal boundaries) to inward-facing surfaces of physical features (i.e. physical boundaries) that enclose indoor spaces. Many studies comprehensively deal with various possibilities of legal boundary position relative

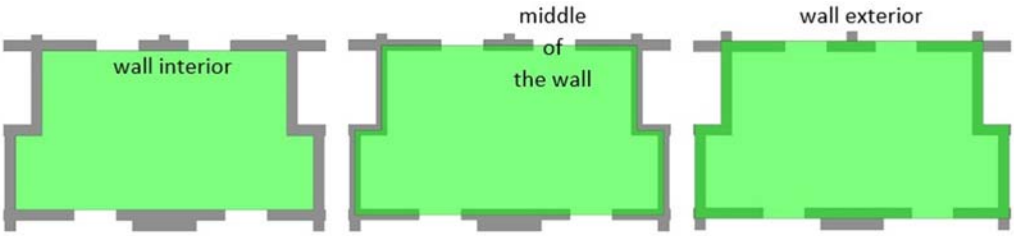

Figure 3 Options for real property unit boundary placement

to physical objects in the building (middle of the wall, wall exterior or interior surface), which in essence depends on each country's legislation (Paulsson 2007). Wang (2015) studies the boundary placement from a 3D visualisation perspective, Atazadeh *et al*. (2017) and Rajabifard *et al*. (2019) discuss the boundary placement in relation to BIM. Therefore, this approach seems to go against the established knowledge and thus requires further justification.

This paper does not intend to argue nor deal much with legal aspects of 3D cadastres, but rather provide a technical view on this matter. There is no doubt that in theory, a legal boundary can be established anywhere in space, not related to any physical features. However, when it comes to registering RRRs in buildings, the physical features become more important, which is also reflected in the number of studies dealing with this matter. Therefore, a legal boundary can lie either on the wall exterior, interior or somewhere in between. Atazadeh *et al*. (2017) discuss these options while studying the purely legal, purely physical and integrated approaches for managing the RRRs for buildings. The purely legal approach excelled in visualisation and querying performance, but proved to be inappropriate for communication of boundaries relative to physical structures. Our model minimises this deficiency by constraining legal spaces to physical structures. Fig. 3 aims to bring a common understanding of the terms wall interior, wall exterior and the middle of the wall for real property unit boundary placement in the context of this study. The same concepts can be found in the International Property Measurement Standards (IPMS 2020) that are developed to overcome the differences between countries regarding the rules for measuring the buildings. In general, if the real property unit boundary is defined by the wall interior surfaces, it does not contain any bounding walls. In contrast, if defined by the wall exterior, it contains all bounding walls. Besides these two cases, we add a case where the boundary is defined in the middle of the wall or anywhere between the inward-facing or outward-facing surfaces of walls; what's more, the boundary might be defined also as a buffer zone – in all these cases an indoor-space can still be used as a core spatial unit which is extended as defined by the law.

Most jurisdictions worldwide use condominium (Paulsson 2007) to manage the RRRs, which is inherently connected with co-ownership since for buildings there are certain spaces that need to be owned by all individual owners (land parcel, common spaces and installations, etc.). The exterior and middle wall boundaries open up several issues and dilemmas regarding RRR management in the building (ownership is used as it represents the most important of the RRRs):

(1) If a boundary of a real property unit is defined in the middle or exterior side of the wall, the wall is owned only by some of the owners. If the wall is statically important, this concerns all individual owners in the building.

(2) If a boundary of a real property unit is defined in the middle of the wall, how is the ownership determined for outer walls that delineate the building interior and exterior?

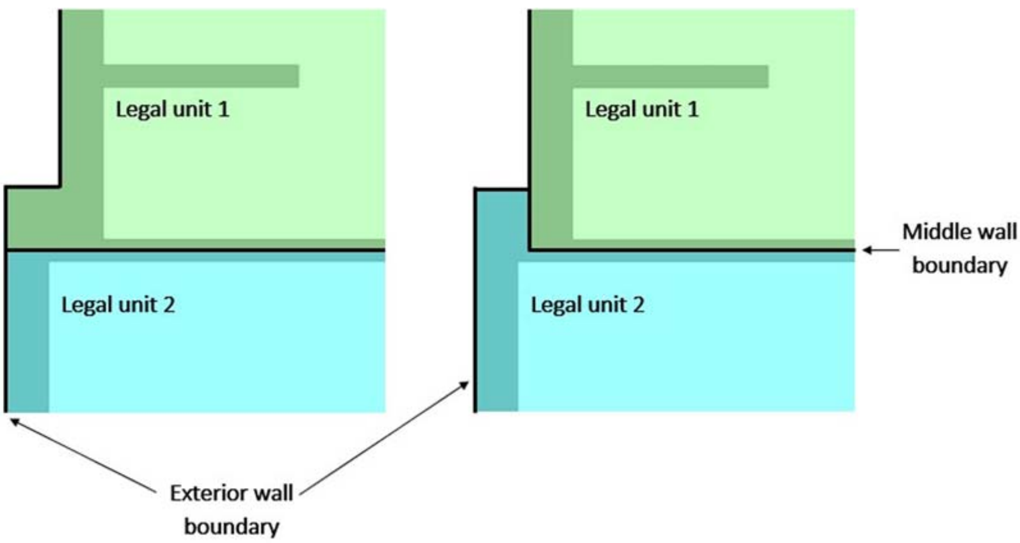

Figure 4 Different variants of exterior boundary placement

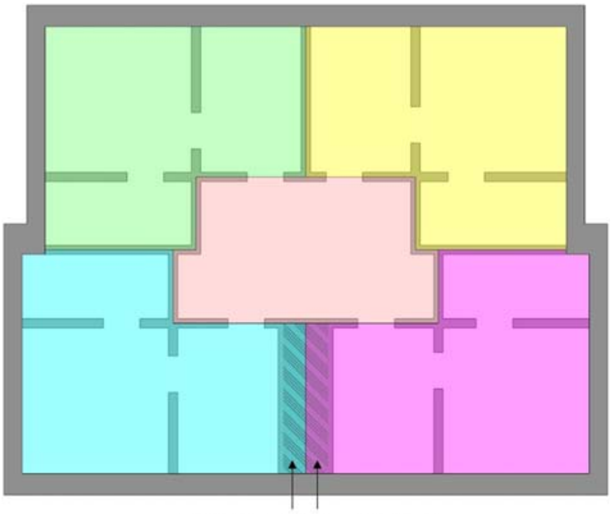

Figure 5 Various sizes of legal units, presented in different colours, for the same apartments (boundaries between real property units lie in the middle of the wall)

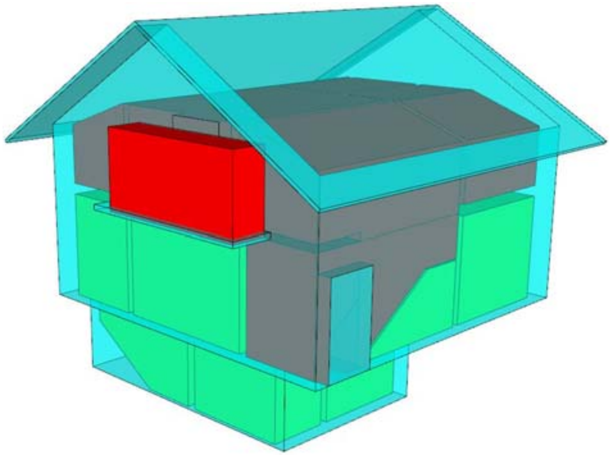

Figure 6 An example of the building geometry with legal amendment (balcony space)

(3) If a boundary of a real property unit is on the exterior side of the wall, how is a boundary in complex situations defined (Fig. 4)?
(4) If a boundary of a real property unit is defined in the middle or exterior side of the wall, how is the ownership of various installations in this wall determined?
(5) If walls have a various thickness and the boundaries of a real property unit are defined in the middle or exterior of the wall, identical physical units have different sizes of their respective real property units (Fig. 5). Should the subject of their ownership be different?
(6) If a boundary is in the middle or exterior of the wall, is it the same with slabs? The slabs provide structural stability for the entire building and thus also concern all individual owners in the building.

All listed dilemmas suggest that individual owners cannot fully exercise their ownership rights on the building structural parts but only on indoor spaces that are provided and made functional by the building structure. There are several legal solutions, for example, the definition of the object to which RRR refer in a contract, where building's structural parts might also be included. However, if we use interior wall surfaces as boundaries of real property units, we avoid the listed dilemmas and issues. This represents a similar concept as the IPMS 3C variant for measuring the buildings in the International Property Measurement Standards (IPMS 2020). Interior wall surfaces enclose indoor spaces which are used as a core spatial unit in our data model. The difference from the IPMS 3C is that the geometries of indoor spaces touch each other at passages, which means they are not exclusively bounded by physical structures.

Apart from already mentioned indoor spaces, the external building, can be characterised as an important entity for registration of RRRs on buildings. The external building geometry should enclose all indoor space geometries. It represents a key feature that delineates the building from the traditional continuous land parcel structure found in most land administration systems. Following the third objective, the model is designed to leave the traditional 2D parcel-based cadastral system mostly unchanged. For integration with 2D parcels, the ground contact area or maximal extent area (or both) of the building can be used. Depending on legal regulations, these areas are restricted to one parcel, form a parcel or can be independent of the parcel structure and only provide the information about the spatial extent of the building. These approaches are well established in most cadastral systems worldwide.

The pure concept of using indoor spaces and building external geometry, enclosing indoor spaces, becomes problematic when dealing with semi-indoor and semi-outdoor spaces that are partly connected to a building, but cannot be characterised as indoor space (Fig. 6). There are countless variants of these spaces (balconies, covered or semi-covered terraces, atriums, etc.). Yan *et al.* (2019) provide a comprehensive study on this matter from a navigation perspective that illustrates that no clear boundary exists between indoor and outdoor space. The determination of what is part of a building and what is not is a general dilemma when dealing with RRR registration on buildings. Our proposed model can be used to register these spaces in a similar way as indoor spaces in Atazadeh *et al.* (2017).

Following the fourth objective, we have designed the implementation of the proposed model in the PostgreSQL DBMS with PostGIS and SFCGAL extensions. The database implementation represents a basis that can be further extended according to the specific needs of each jurisdiction. The selected DBMS supports 3D spatial data types, including solid geometries. Additionally, it offers functions that support the stored 3D data management and analyses.

Data model concept

Based on the objectives, we develop the data model concept (Fig. 7), defined by the main entities, their relations and their geometric representations. Compared to the data models that are referenced in section 2, our model can be perceived as basic. The reason for this is that this model is used to present and discuss the idea of using indoor spaces as the core cadastral data modelling entity, not to provide a complete and all-inclusive data model.

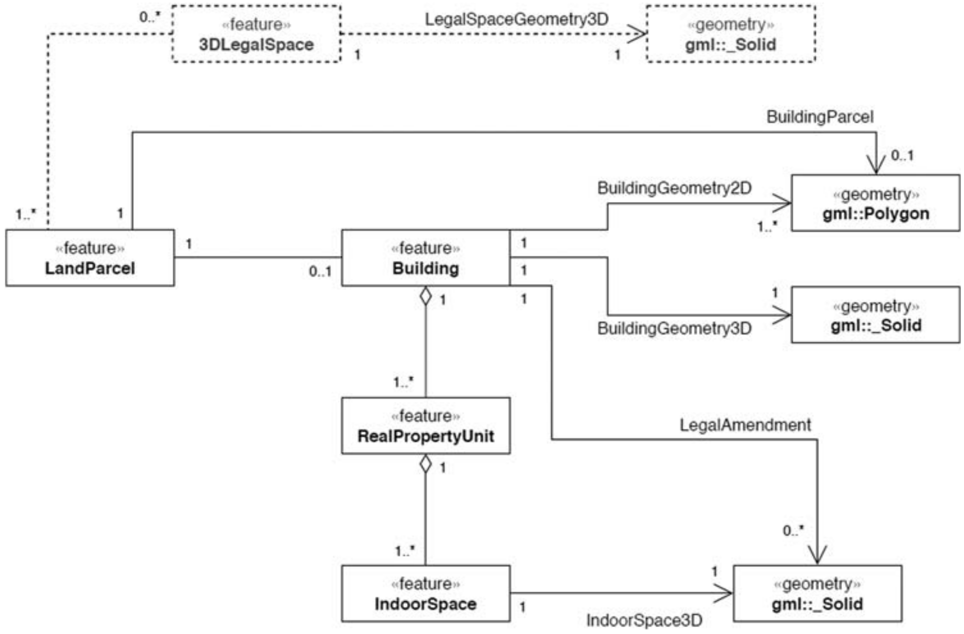

Figure 7 The concept of the proposed cadastral data model for buildings

3D building modelling for cadastral purposes is the main focus of this paper. However, the presented concept also includes the relation to the land parcels and the optional relation to the 3D legal spaces, which are not defined by physical features. The proposed concept assumes that each building is associated with at least one real property unit, but this depends on the jurisdiction and can be altered. For buildings where no condominium is established, only basic data or no data is collected.

The data model is aligned with the LADM (Fig. 8). RealPropertyUnit is related to the LA_BAUnit class and IndoorSpace to LA_SpatialUnit and its subclass LA_LegalSpaceBuildingUnit. However, LADM explicitly denies the restriction of legal spatial units to the building's physical structures (Lemmen *et al.* 2015), which differentiates the two models. As the focus of the proposed data model is on indoor spaces, the solid representation of the geometry is selected as the most appropriate. It facilitates 3D representation, spatial analyses and provides volumetric information (Rajabifard *et al.* 2019), while LADM provides geometric representation of 3D geometries by boundary faces.

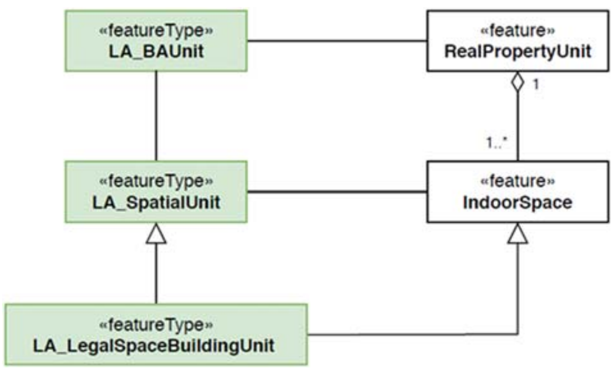

Figure 8 The relation of the proposed cadastral data model (white) and LADM (green) classes

Despite the differences, the proposed data model is partly compliant with the 3DCDM data model (Aien 2013) and the extended Core Model for 3D cadastre proposed by Knoth *et al.* (2018). Both models use an integrative approach and represent physical features using multiple entities. However, if the same concept of using indoor spaces to define the real property units is used, the data models would be similar to the one that is proposed in the paper.

Results

DBMS implementation

A DBMS represents the technical backbone of cadastral (information) systems worldwide. It provides an efficient way for secured storage and maintenance of cadastral data as well as for exploitation of cadastral data and information. Each new solution or upgrade of cadastral systems should, therefore, include or be supported by an advanced DBMS. Spatial data storage and maintenance are supported by the majority of DBMSs considering the ISO SQL/MM-Part 3 (ISO 2016) or OGC Simple feature access (OGC 2010), providing spatial data types, spatial indexes and operations that allow the geometry of the objects to be stored alongside their thematic attributes. The proposed cadastral data model is implemented using open source DBMS PostgreSQL with PostGIS and SFCGAL extensions, which support storage of polyhedral surfaces and solids, and offers functions to perform 3D operations. Three main tables (Fig. 9) are used to represent three core features of the presented concept (Building, RealPropertyUnit and IndoorSpace).

Although the selected DBMS supports storage of solids, the internal holes are not fully supported. The polyhedral surfaces can be stored with internal closed boundaries that form holes. However, 3D operations require solid geometries, obtained by the ST_MakeSolid. The polyhedral surfaces with an internal hole(s) cause the ST_MakeSolid function to crash with an invalid geometry error. This is

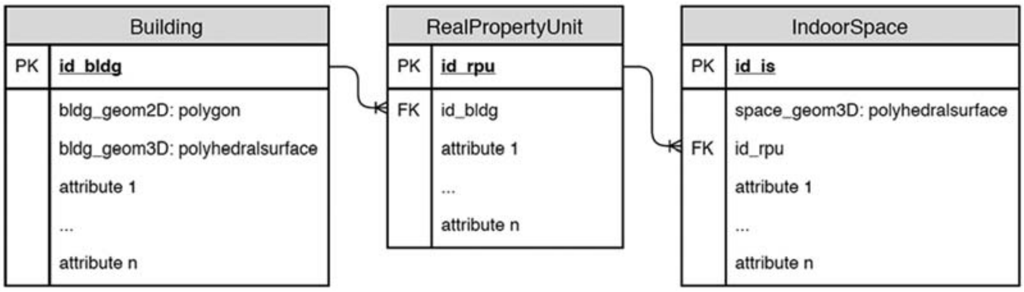

Figure 9 **DBMS implementation of the proposed cadastral data model**

not a problem in our case, as indoor spaces are bounded by physical structures. A hole in the indoor space would mean the physical structure would be detached and would 'hover' in space. The hole in indoor space could be created only by another indoor space that belongs to the other real property unit in the same physical indoor space. Similarly, the building external volumetric representation does not need internal holes, as an internal hole would still be indoor and not outdoor space. Despite this, we present the extension of the basic implementation that can accommodate holes in 3D solids. The database schema presented in Fig. 10 introduces two new tables that can store several solid objects for one Building or indoor space representation. The hole Boolean type attribute indicates whether the geometry represents a hole.

The CityGML standard widely introduced the concept of modelling of spatial entities in a 3D environment with multiple levels of detail (LOD). There are several benefits of this approach, such as efficient visualisation and data manipulation, and efficient spatial and other analyses that can also be identified as important by cadastral authorities. The extension (Fig. 11) can accommodate multiple levels of detail for both indoor spaces and outdoor geometry by adding an attribute that identifies the corresponding level of detail for each geometry. The concept of multiple LODs is useful for cadastral authorities to store additional, more detailed data to further clarify the RRR situation in the building.

Data model integration

Registration of a building in the cadastral system, i.e. land administration system, represents one of the few available instruments for public authorities to obtain accurate, structured, relatively detailed spatial and thematic data about buildings, including data about the indoor environment, which is not accessible through remote sensing technology. Cadastral data has often been used for multiple purposes beyond its core one, partly so that the high costs of establishing and maintaining the system can be spread and justified, and partly because it has been the only available data source. If the cadastral data is structured so as to enable integration with data from other related domains, it can significantly increase its potential applications and consequently, its importance and value. Therefore, one of the most important objectives of our research has been to develop a cadastral data model for buildings that can be integrated with the dominant standards relating to 3D building modelling. The integration or at least linking is important to the data input side, i.e. to obtain data for registration from various data sources, and to the data output side, i.e. to include or use the 3D cadastral data in other models and increase the cadastral data usage/application potential.

Integration with IFC

The importance of integrating land administration processes and BIM is increasing with the rapid adoption of BIM in the AEC industry. Several studies have already analysed various options for the integration of BIM and cadastral data (El-Mekawy and Ostman 2012, Liu *et al.* 2017, Oldfield *et al.* 2017, Rajabifard *et al.* 2018, Atazadeh *et al.* 2019, Rajabifard *et al.* 2019). All studies identified the IfcSpace as the most important class for the integration

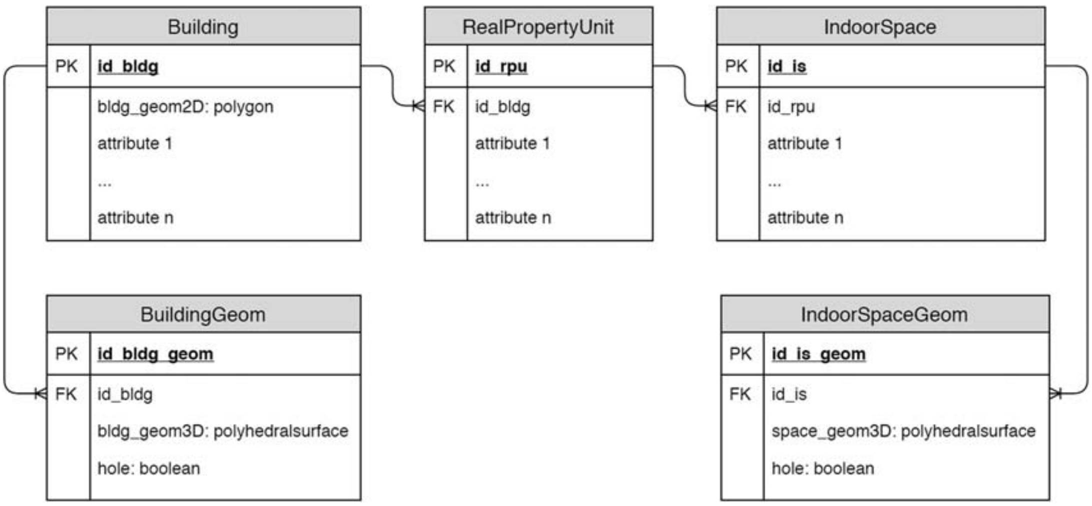

Figure 10 **DBMS implementation allowing storage of solids with holes**

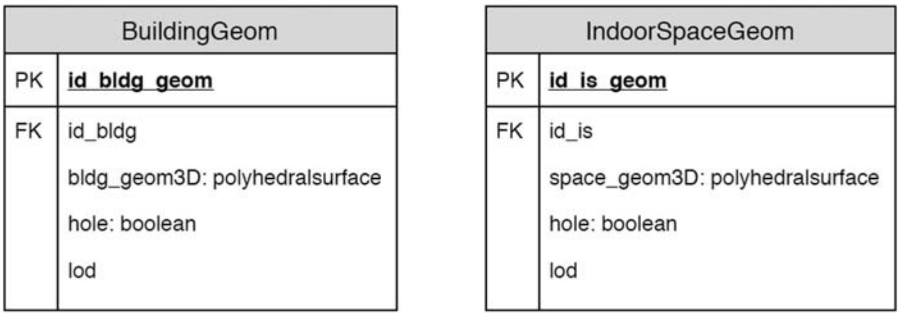

Figure 11 DBMS implementation allowing storage of multiple levels of detail

of IFC with RRR data. Atazadeh *et al.* (2019) propose an approach that uses IfcSpace and IfcZone classes and is aligned with our modelling approach. The authors establish a link with LADM classes, by linking IfcSpace with the LA_LegalSpaceBuildingUnit class and IfcZone with LA_BAUnit (Fig. 12). This indicates that our proposed cadastral data model can be integrated with IFC data.

Integration with CityGML

CityGML is the dominant standard for 3D topographic modelling in the geospatial domain. The CityGML standard defines five LODs that increase in their geometric and semantic complexity. An interesting data model specification as an extension of LODs for detailed building modelling was proposed by Biljecki *et al.* (2016), where a set of 16 LODs focused on the grade of the exterior geometry of buildings, while the indoor space was not discussed. Since the introduction of CityGML 2.0 in 2012, the standard has also been intensively studied from a 3D cadastral perspective. Çağdaş (2012) proposed a CityGML extension for property taxation. Góźdź *et al.* (2014) proposed an ADE for the CityGML standard to link it with LADM classes, which is further studied by Li *et al.* (2016). The authors propose linking the

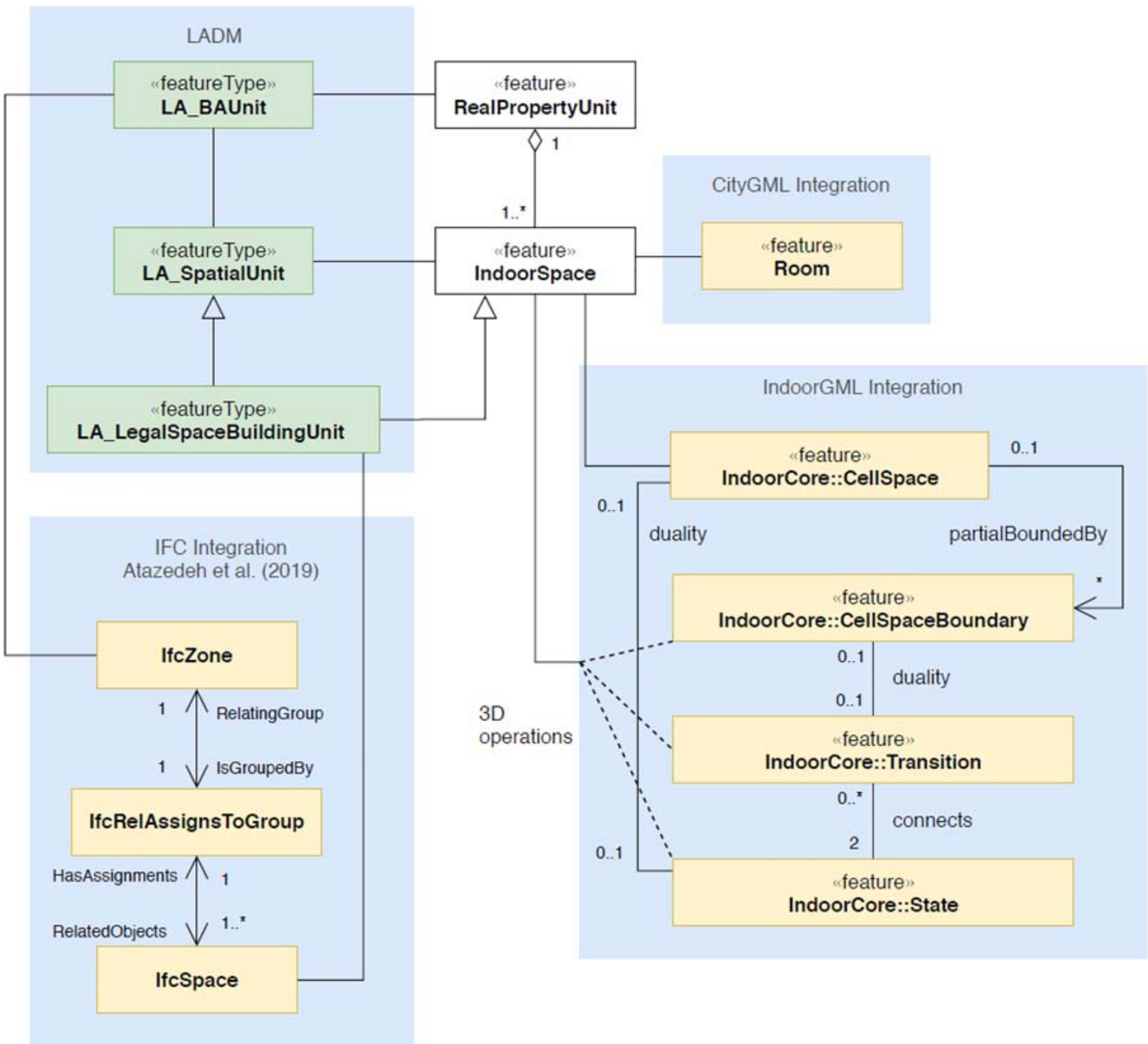

Figure 12 The concept of the integration of the proposed data model with the IFC, CityGML and IndoorGML standards

LADM LA_LegalSpaceBuildingUnit class with a legal object class that is related to the BuildingPart and Building classes. Ying *et al.* (2017) use CityGML LOD 3 models to construct volumetric objects, suitable for use in 3D cadastres.

As the core element of our model is indoor space, the corresponding class in CityGML is the Room class. Like the indoor space in our model, the Room class has a solid geometry representation (Fig. 12). However, the Room class can be included only in the LOD 4 model, where very detailed physical structures are required. Up to LOD 4, the CityGML standard does not provide an option to model the building interior. Boeters *et al.* (2015) emphasise the need to include indoor geometries to lower levels of detail. The building geometry, on the other hand, can be better integrated with CityGML. Unlike the Room class, the _AbstractBuilding class is not restricted to specific levels of detail.

Integration with IndoorGML

Of the three standards considered in this section, the IndoorGML has the simplest data model. To avoid duplications, the standard allows linking with IFC and CityGML. The main role of IndoorGML is to provide a data model for indoor navigation purposes. Zlatanova *et al.* (2016) and Alattas *et al.* (2017) studied the link between LADM and IndoorGML to provide additional information about indoor spaces which can improve indoor navigation performance. Rajabifard *et al.* (2018) discussed the options for linking IndoorGML with LADM and concluded that IndoorGML cells could be used to define the geometry of legal spaces. To realise this, the authors emphasise the need for investigation of complex 3D spatial analyses. Our approach is very similar, and we addressed the need for 3D spatial analyses by implementing the model in PostgreSQL with PostGIS and SFCGAL extensions that provide state-of-the-art DBMS support for 3D spatial operations.

As in the proposed model, the core element of the IndoorGML data model is the indoor space (CellSpace class), which makes the two very aligned and interoperable in this aspect (Fig. 12). Following the duality concept, the IndoorGML data model contains navigation graph elements – nodes and edges (State and Transition elements), which are not included in the proposed cadastral data model. The indoor space geometries in the proposed model touch each other on the surfaces that represent the passage between them (doors and other openings). This makes it possible to derive the indoor space topology from geometries using 3D operations available in the selected DBMS. If the physical indoor space is divided into several touching indoor spaces belonging to different real property units, these can be used to perform subspacing of IndoorGML CellSpace entities.

Discussion

The legal frameworks that regulate the registration of RRRs on buildings differ very much among the countries and jurisdictions. The data model is focused on the definition of real property units using indoor spaces, independently on the legal definition of a real property unit. As already mentioned, the legal regulations do not require the borders of the real property units to coincide with the borders of indoor spaces. Therefore, the proposed data model cannot be directly introduced and implemented without amendments of the legal framework or the proposed data model. The proposed data model can be amended with an additional entity, which represents the building's physical features. These features are linked to the corresponding real property unit the same way as indoor spaces. Using this amendment, the model can support all types of boundaries of real property units within the buildings, while still allowing the presented geospatial data integration options. On the other side, the legal frameworks can also be amended to increase the compatibility with the presented data model. These amendments are mostly related to the definition of the RRRs on the physical features of the building (walls, slabs, etc.). One option is to define that all the physical structures of the building are owned by all the owners, if not additionally defined differently. Another option is to define that the physical structures between two indoor spaces of the same real property unit also belong to this real property unit. The physical structures between two indoor spaces of different real property units can be defined as owned by both owners, or owned by each owner to the middle. The data model can also be modified to allow the modelling of only the outer boundaries of the real property units. The geometry of the real property unit can be defined as a union of all adjacent indoor spaces belonging to the same real property unit, also containing all physical structures of the building. In case the indoor space geometries would be sourced from the BIM entities, this union should be done additionally using 3D modelling software. If the indoor spaces are modelled based on measurements, then all the spaces of the same real property unit can be joined into one 3D geometry representing the extent of the real property unit. However, this would reduce the options for integration with other data models and consequentially the options to use the cadastral data for other purposes.

One of the challenging topics regarding RRR registration on buildings and parts of buildings within a 3D cadastre is the required geometric accuracy as well as the level of detail of the geometric data model. This research does not deal with this issue apart from allowing storage of multiple levels of detail. If the boundaries of legal spaces coincide with physical boundaries, the required accuracy is not as high as it is for boundaries with no physical counterpart. In the future, the BIM models will provide very detailed data on the building's physical elements for more and more buildings. The integration, as presented in this study, will therefore be very beneficial. The current problem is that many IFC models do not provide as-built data, essential for cadastral registration.

The developed data model is based on indoor spaces that are touching each other at passages, which means that 3D geometries of indoor spaces have shared faces. The proposed database implementation uses the polyhedral surface to represent each indoor space, which means the 'touching' faces are duplicated. Consequently, the required storage space is increased. Additionally, the duplication can cause the data to be inconsistent. However, this approach has several advantages over storing 3D geometries using the topological data structure.

(1) The 3D geometries can be managed by the available database 3D functionalities.
(2) We have direct access to 3D geometries, without the need to construct 3D geometries using lower-dimensional geometrical features and their topological relationships.
(3) The 3D geometries can be stored in line with other attribute data.

The inconsistencies should be avoided by automatically checking the data at insertion and each manipulation of geometry. The PostgreSQL DBMS with PostGIS and SFCGAL extensions has functionalities to implement some data validation as an overlapping check also in 3D.

The open question for cadastral building registration is which buildings to include. While in many countries detailed cadastral registration is foreseen only for buildings where a condominium is to be established, some countries, e.g. Slovenia and Sweden (see Drobež *et al.* 2017, Larsson *et al.* 2020), register all buildings, mainly for efficient real property valuation that serves many governmental applications. In this case, the indoor spaces have to be measured to obtain the area information. With some additional vertical measurements, it is possible to obtain enough information for 3D modelling of the indoor spaces according to the proposed data model. This also opens new possibilities for valuation as we obtain not only area but also the volume of the indoor spaces.

For the buildings with no established condominium, all indoor spaces can be grouped into one real property unit. Following this concept, also these buildings can be modelled according to the proposed data model. If the cadastral system registers only the buildings with multiple real property units, only some basic data may be registered about the other buildings (e.g. external geometry) or they can be entirely left out. The buildings having multiple real property units can be modelled according to the proposed data model.

However, it should be noted that the developed concept and data model is in accordance with the current practices of RRR registrations on parts of buildings, e.g. condominiums, based on floor plans.

Storing detailed data on the interior of buildings can be problematic from a privacy and security aspect. This can be efficiently managed by making parts of the data (indoor spaces) available only to authorised users. Given that the proposed model offers data that can be used for many applications, including public safety, crisis and disaster response by police, firefighters, ambulance and other first responders, the benefits should outweigh the concerns.

Conclusions

In our study, we look for generic solutions to 3D cadastral building modelling that would be suitable for deployment in various jurisdictions. The idea of using indoor spaces constrained to physical features as the core element for cadastral registration of buildings is used for 3D cadastral modelling. Using the indoor space as the core spatial unit differentiates the research presented here from other related studies that have included indoor spaces in the data models. The model design process is thoroughly discussed, with references to the initial objectives used to steer and guide the model design process. The contribution of this study can also be perceived in the presentation of a complete design process from initial idea to DBMS implementation. The aim of the study has not been to reject all the proposed 3D cadastral models and research in this field, but to provide an alternative data modelling approach. The data model is designed to be aligned with the LADM standard and standards related to physical modelling of buildings. This means it enables and facilitates the integration of cadastral data with the data from other related domains, which is becoming increasingly important. It can be considered and applied by the cadastral authorities in revising or designing new cadastral data models with objectives aligned with the ones presented in this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Javna Agencija za Raziskovalno Dejavnost RS: [Grant Number P2-0406 Earth observation and geoinformatics]; Minsitry of Environment and Spatial Planning of the Republic of Slovenia (Surveying and Mapping Authority of the Republic of Slovenia): [Grant Number V2-1934].

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Cadastral data as a source for 3D indoor modelling

Tekavec, J., Lisec, A. (2020a)

Land Use Policy, 98(2020): 1-14

DOI: 10.1016/j.landusepol.2019.104322

Faktor vpliva za leto 2019: 3,682 (Q1)

Land Use Policy 98 (2020) 104322

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Cadastral data as a source for 3D indoor modelling

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ARTICLE INFO

Keywords:
IndoorGML
3D cadastre
Real property
Floor plan
3D modelling

ABSTRACT

Despite the rapid development of indoor spatial data acquisition technology, there are currently no solutions that enable large-scale indoor spatial data acquisition due to several limiting factors that characterize the indoor space. This fact, together with the rapidly growing need for indoor models, is the main motivation for our research. The focus is on the study of the appropriateness of existing cadastral data for 3D indoor modelling. Within the study, a framework for 3D indoor modelling has been developed, comprising a chain of processes, starting from initial cadastral data and ending with the OGC IndoorGML compliant document. The process chain is divided into three parts, which are described individually and supported by UML activity diagrams. The Slovenian Building Cadastre data represents the basis for the framework design and data assessment. The IndoorGML standard is used for final outputs, as it provides a standardized data model for the representation and exchange of indoor spatial information designed for indoor navigation and location-based services. The data storage options using a spatially enabled database are presented for storing 2D and 3D geometries. The stored data enables fully automatic IndoorGML document generation on request, while also taking advantage of all spatial database functionalities. The proposed approach is software independent and can be implemented with various spatially enabled software packages. In addition to 3D indoor data modelling, the framework represents a comprehensive method for assessing the usability of input data for the purpose of 3D indoor modelling. The assessment is done for the case of the Slovenian Building Cadastre. The assessment of the cadastral data suitability for 3D indoor modelling can be used for decisions regarding future steps towards a multi-purpose 3D real property cadastre. The presented concept can be applied in many countries worldwide that have a similar condominium registration system.

1. Introduction

The importance of 3D indoor models is growing due to a variety of applications, related in particular to location-based services and navigation (Afyouni et al., 2012; Yang and Worboys, 2015; Lin and Lin, 2018). We are often faced with locating points of interest (POI) and finding optimal paths to them, which can be effectively solved by using navigation principles. The navigation process requires two key components. The first one is positioning and the second one is spatial data, which provides the spatial context to the position information. Combining these two components, the navigation device can calculate an optimal route to the desired POI.

Recent technological developments in the field of geospatial data acquisition and outdoor positioning have made location-based services highly affordable and widely available on smartphones and other electronic devices (Huang et al., 2018). However, this is only true for the outdoor environment, as technologies for geospatial data acquisition, including remote sensing, and technologies for positioning, in particular Global Navigation Satellite Systems (GNSS), cannot be used in the indoor environment. As a result, there are a great number of highly developed and massively used location-based services (LBS) for the outdoor environment, such as Google Maps, Uber, Foursquare, Pokemon Go etc., and almost none for indoor space. Looking at the market of outdoor LBS, one can easily see the great potential of indoor LBS, especially because nowadays we spend a major part of our time indoors, whether working, resting, exercising, shopping, etc. The indoor navigation applications are of particular interest with regard to public buildings (e.g. hospitals, schools, universities, bus and railway stations, etc.) and shopping centres to facilitate POI searching for their visitors. Apart from that, several public services are potential users of indoor spatial data (e.g. police, emergency medical aid, firefighters, etc.). These services would benefit from indoor spatial data of every type of building, not just the public ones. Some studies have evaluated the indoor 3D spatial data and indoor navigation support for first responders in emergency situations (Lee and Zlatanova, 2008; Tang and Ren, 2012; Chen et al., 2014; Tashakkori et al., 2015). The potential has

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https://doi.org/10.1016/j.landusepol.2019.104322
Received 2 April 2019; Received in revised form 14 October 2019; Accepted 21 October 2019
Available online 22 January 2020

expanded even more in recent years with the increasing use of smartphones, which combine portability, computing power, data storage, connectivity and sensors.

Several technologies are being developed to enable efficient indoor spatial data acquisition using various combinations of passive image sensors and active ranging sensors (Gunduz et al., 2016; Kang and Lee, 2016; Liang et al., 2016; Jiao et al., 2017; Lee et al., 2017; Lenac et al., 2017). Indoor positioning is also a rapidly evolving field with some technologies already available and a lot of ongoing research activity (Vanclooster et al., 2016; Correa et al., 2017; Brena et al., 2017). The major common problem of both spatial data acquisition and positioning technologies related to the indoor environment that sets them apart from technologies for outdoors is that they are currently spatially very limited, i.e. they cannot be performed on a large scale. In practice, this means that each building must be individually equipped with an indoor positioning system, and a detailed as-built 3D model of the building interior structure should be available. In addition, the model has to include the topology information, i.e. an indoor space connectivity graph.

The complexity and consequently high costs of indoor spatial data acquisition noted above justify research on the usability of already acquired and stored data for existing buildings. The most detailed and comprehensive documentation about buildings is a construction plan. For older buildings, the drawings and documentation were provided and archived in analogue form, while for newer ones digital vector models are provided, and for some recently built ones also conforming to the standards in the fields of Building Information Modelling – BIM (ISO, 2018). Construction models that are provided within BIM in accordance with the Industry Foundation Classes (IFC) provide rich 3D geometry and semantic information, which can be used, analysed, enriched and updated by a large range of domains included in a building's lifecycle. This also includes the field of indoor LBS, which can benefit from the growing utilization of BIM in practice. Much recent research is therefore focused on integration of BIM and geospatial domains to fully exploit BIM potential in the geospatial domain and vice versa (Li and He, 2008; Chen et al., 2014; Hong et al., 2015; Deng et al., 2016; Diakité and Zlatanova, 2016a,b; Xu et al., 2017; Teo and Yu, 2017; Ellul et al., 2018). Currently, BIM has not yet been widely introduced operationally into the processes of building design, construction, maintenance, and facility management, but in the future, it has big potential to become a valuable data source for indoor LBS. The biggest issues surrounding the use of building construction documentation and data for indoor data extraction lie in their complexity, and in the fact that generally, they do not provide as-built information about new buildings (Atazadeh et al., 2017). Another possible source of data about buildings, albeit lacking in detail, is land administration data. Although their content, structure, degree of detail and entry regulations depend on each country's legislation, this data is generally centralized and easier to access compared to construction documentation.

This article focuses on 3D indoor modelling of buildings using cadastral data as an alternative data source to other indoor spatial data acquisition approaches. In this way, the article also aims to contribute to the idea of a multipurpose 3D cadastre (Tekavec et al., 2018), offering data modelling approach for indoor location-based services. We decided to use cadastral data from Slovenian Building Cadastre, as it has several advantages over other data sources in Slovenia, in particular, the centralized storage, availability and relatively uniform data content are the most important ones. Our aim has been to develop a framework for 3D indoor modelling which could be applied to Slovenian cadastral data. It is designed to generate 3D indoor models, compliant with IndoorGML standard, that provides a data model for indoor spatial information. The framework can be used for two purposes, either to generate 3D indoor models or to assess the input data suitability from the perspective of 3D indoor modelling. The latter can provide valuable information for decision making regarding the future changes of data models and processes in land administration systems. The article represents an extension of the research, published at 6th FIG Workshop on 3D cadastres (Tekavec and Lisec, 2018). The whole framework was thoroughly revised, and the proposed process has been modelled using UML activity diagrams. The research is supplemented with a comprehensive study on various options for data storage in a spatial database. Additionally, 3D data visualization options are presented and discussed.

2. Literature review

In recent years, the topic of indoor LBS has been experiencing intensified attention in research as the services and available technologies lag behind compared to the ones developed for the outdoor environment (Jensen et al., 2010; Gunduz et al., 2016). Important factors that facilitate research and development and ensure their consistency are international standards. There was no specific standard in the field of indoor LBS until the Open Geospatial Consortium (OGC) standard IndoorGML was introduced in 2014, aiming to harmonize and foster research and development. IndoorGML standard provides an open data model and XML schema for indoor spatial information (OGC, 2014). It covers geometric, topological and semantic aspects of indoor space. The origins of the standard date back to the year 2009, when the multilayered space-event model for navigation in indoor spaces was published by Becker, Nagel and Kolbe (2009). They defined key principles that are used in the IndoorGML standard. The standard follows the cellular space concept, according to which the indoor space is modelled as a collection of non-overlapping cells. This sets it apart from the other standards in the field of 3D modelling (e.g. CityGML, IFC) as they do not model the indoor space itself, but the building features (e.g. walls, windows), which, on the other hand, can also define indoor space. The most similar class, named IfcSpace, is used in IFC to represent empty spaces inside the building and can be used for linking the two standards (Teo and Yu, 2017). The overlap with other standards in the geometric part is solved with the possibility to add external references. However, 3D geometry can also be included in an IndoorGML document.

Topology is the key component of the IndoorGML standard, as it is vital for navigation applications (Lee, 2004). It is realized in the form of a Node-Relation Graph (NRG). The theoretical basis for derivation of NRG from the indoor space geometry is the Poincaré duality, where a k-dimensional object in N-dimensional primal space is transformed to an (N-k) dimensional object in dual space (Munkres, 1984). The topological relationships in IndoorGML are explicitly described using the XLinks concept of XML provided by GML. The referencing is realized using *href* attributes (*xlink:href* is used in the paper). Another important concept of the IndoorGML standard is a multi-layered representation (Becker et al., 2009). It allows the same indoor space to be modelled in several layers according to the cellular space concept and therefore allows for separate modelling of WIFI, RFID and other spaces related to indoor navigation (Fig. 1). The links between spaces are established via interlayer relations with different possible relations, such as within, contain, overlap.

With the introduction of the IndoorGML standard, the research community and developers got a data model to develop interoperable solutions for indoor LBS. Since then, several studies relating to this standard have been done on data acquisition, 3D modelling, visualization and applications. Seo (2017) developed a software for creating IndoorGML compliant models, which is is similar to our proposed framework in terms of data input and output. However several differences between them exist, which are discussed in section 5. Ryoo et al. (2015) compared the OGC standards IndoorGML and CityGML (OGC, 2012),

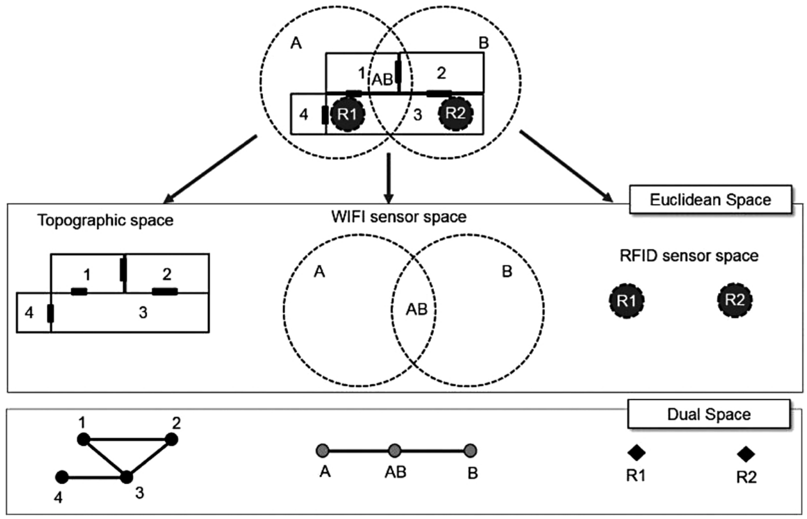

Fig. 1. IndoorGML multi-layered representation (OGC, 2014).

which both cover 3D modelling of indoor space in the GIS domain. Although they are similar in the 3D modelling aspect, the authors showed their differences, especially in their scope and applications. Typically for rapidly developing fields, there are a large number of remaining unresolved issues regarding indoor mapping and modelling. These issues are systematically analyzed and categorized into existing and future ones in Zlatanova et al. (2013). Recently Kang and Li (2017) emphasized the potential of the IndoorGML standard and encouraged the research community to include it in their research by proposing new features, developing new extensions and performing case studies. Research has also been conducted in relation to the data sources and modelling processes for obtaining IndoorGML compliant models (Khan et al., 2014; Mirvahabi and Abbaspour, 2015; Kim and Lee, 2015; Diakité and Zlatanova, 2016a,b; Teo and Yu, 2017). Indoor spatial information is related not only to physical structures but can also be combined with legal information (Zlatanova et al., 2016; Alattas et al., 2017). These studies deal with linking IndoorGML and LADM (ISO, 2012) mostly on a conceptual level. Alattas et al. (2018) further propose a database implementation of the conceptual link between LADM and IndoorGML. The main aim of linking is to analyse how legal information from LADM can improve the semantic properties of IndoorGML models and thus improve the process of indoor navigation. The cadastral extension is also mentioned as a candidate for the semantic extension of IndoorGML in Kang and Li (2017). The link between land administration and IndoorGML has therefore already been established and studied, but until now only at a conceptual level.

3. Research methodology and materials

The design of a conceptual framework for 3D indoor modelling based on cadastral data represents the core of the presented research. The framework is composed of a chain of manually or automatically performed processes, starting from initial cadastral data in the form of floor plans in raster format. The attention is given to minimize the need for manually performed activities, as they significantly increase the amount of resources needed for execution of the implemented framework. The OGC IndoorGML standard is used for final outputs. The framework consists of three main parts that are described in detail in Section 4.

The UML activity diagrams are used to summarize and clarify the framework (Figs. 3, 4, 7 and 14). The diagrams follow the division of the framework into three parts. Each diagram presents the activities and their links in the corresponding part of the framework. Aiming to design an applicable framework, we have tested each process using the input data from the Slovenian Building Cadastre in the form of a floor plan of a residential house. The data is in raster format, containing a floor plan for each storey (see also Drobež et al., 2017). Similar floor plans are usually included in the documentation for condominium registration in several other countries. GIS and ETL tools were used for the implementation of the framework. Besides the output in IndoorGML format, we developed options for 2D and 3D database data storage. The storage can serve as a final output or as an intermediate step from which the rest of the framework to obtain IndoorGML file can be done automatically on request at any given time. For the Slovenian study case, a usability analysis for 3D indoor modelling was further conducted, aiming to identify advantages and disadvantages of the data used throughout the process.

The framework is developed and illustrated based on the Slovenian Building Cadastre data. The Slovenian Building Cadastre was introduced in 2000 as a database for condominium registration in the Land Registry (see also Drobež et al., 2017). In the following years, up to 2006, photogrammetric acquisition of 2D outlines (outdoor) for all buildings was conducted for the whole country. In addition to building outlines, additional attributes were collected, including the ground height and maximum height. In 2006, the Building Cadastre was legally and operationally introduced and detailed registration of buildings and their parts (legal subdivision), together with floor plans, became mandatory. The Building Cadastre data is open and publicly available via the official website. The scanned building registration documentation with floor plans is not publicly available. However, it is available to the authorized land surveyors.

In this study, we have used floor plans from the building in the Building Cadastre, which have been available in raster digital form (Fig. 2) for more than a decade. The vector form of floor plans has been required for new cadastral entries since 2018. Mandatory content of floor plans are outlines of building parts for each floor. In many cases, the documentation contains more detailed floor plans with room outlines aiming to clarify the building division into building parts.

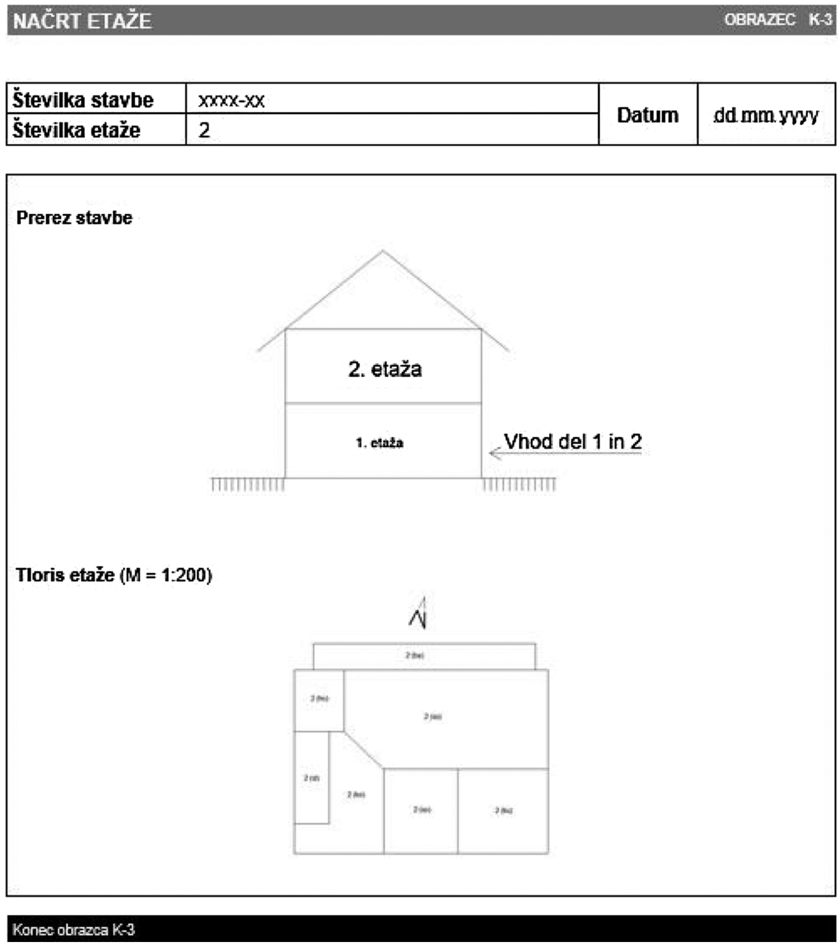

Fig. 2. Sample document of Slovenian Building Cadastre containing the building floor plan.

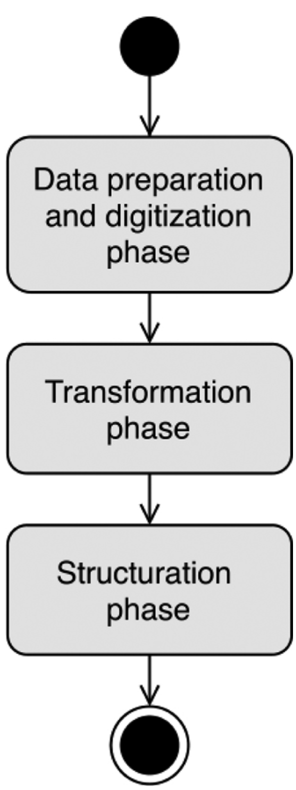

Fig. 3. Generalized UML activity diagram of the proposed framework.

4. Framework design

In this section, the entire process chain of the framework is described in detail. The framework is based on the research, published in Tekavec and Lisec (2018). The division into three parts follows the actual workflow of the framework implementation (Fig. 3).

4.1. Data preparation and digitization phase

In the first phase, all the data should first be acquired, prepared and then digitized. Additionally, the attributes, necessary for the execution of processes in the next phases, have to be added. Fig. 4 presents the processes that are executed in this phase.

For the implementation, we took raster floor plans of a residential house (with outlines of all rooms) modelled to fit into Slovenian Building Cadastre. Generally, two types of floor plans exist, depending on whether or not the wall thickness is considered (Fig. 5). The IndoorGML standard treats both concepts (thin-wall and thick-wall) as valid.

Based on the available digital raster image (floor plan), the geometry and topology (room connectivity) of indoor spaces can be obtained through digitization (Fig. 6). First, we scaled the raster images to represent the true extent of the building. For each floor plan, we created three spatial layers to be able to later align the digitized data to the IndoorGML data structure: a polygon layer for room geometry, a line layer for connections (graph edges), and a point layer for graph nodes. As the IndoorGML standard does not allow cell overlapping, each room outline digitized using the polygon feature, representing the basis for 3D cells, has to be checked for overlap with other polygons. This can be

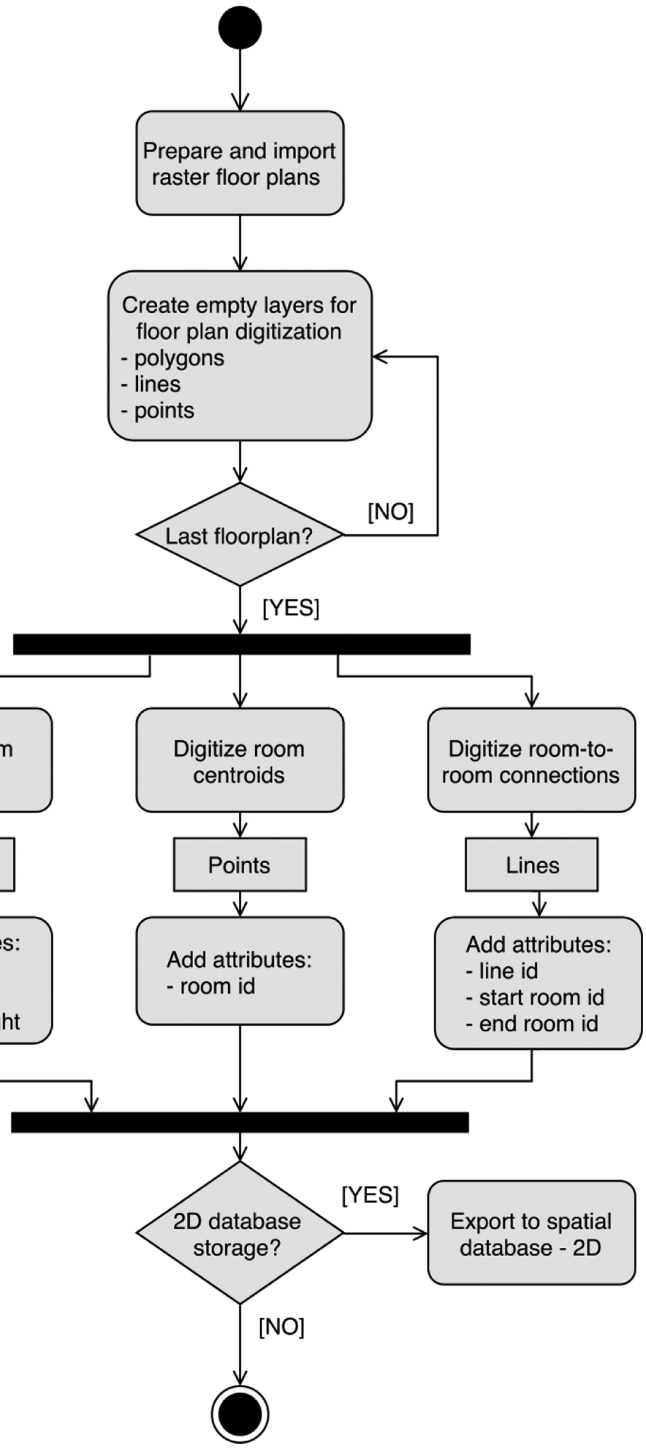

Fig. 4. UML activity diagram for the digitization phase of the proposed framework.

done automatically in QGIS software by the Topology Checker tool. To enable the construction of 3D cell spaces with the extrusion, the floor and ceiling heights have to be added for each floor. These attributes had not been available in Slovenian Building Cadastre until recently (2018) so the heights have to be measured and added manually. The heights can be relative, absolute or a combination of both. For absolute vertical positioning of the model, we need one height that has both relative and absolute height. Navratil and Unger (2013) provided a comprehensive overview of heights in land administration. It is worth mentioning that polygon extrusion could produce overlapping of 3D cells in cases where the floor and ceiling are not straight and horizontal.

Once the room polygons are created, points representing graph nodes can be created automatically as centroids, while lines representing graph edges have to be added manually if the floor plan does not include door openings. The possible connections between spaces can be automatically narrowed down to connections between neighbour spaces, but the actual connections still have to be added manually. Together with floor and ceiling heights, this represents significant manual input as it requires physical inspection of the building. If the floor plan contains the connection openings, they can be automatically identified using object recognition techniques on a raster image. Due to the duality concept, the points are given the same identifier as room

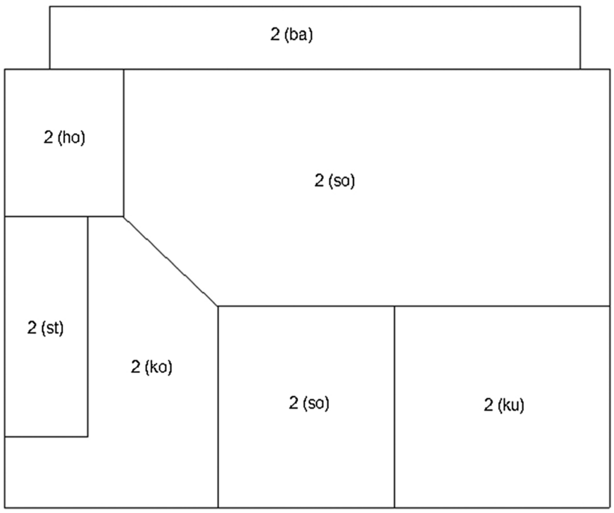

Fig. 5. Raster floor plan from Slovenian Building Cadastre following the thin-wall concept - the room annotations consist of building part number and room usage code in brackets.

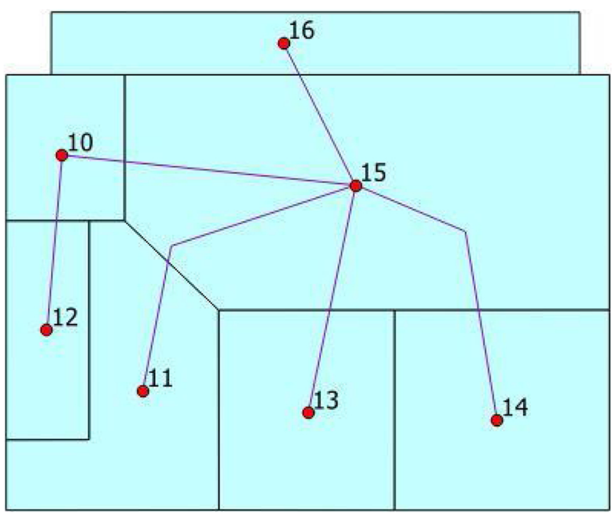

Fig. 6. Digitized polygons, line strings and points with identifiers.

polygons. Each line should be snapped to the start and end point with the start and end point identifiers added as attributes. The lines representing connections between rooms in different floors (stairs and elevators) have to be snapped to points on different layers with both point identifiers added as attributes. This enables the integration of separate connectivity graphs into one graph for a multi-storey building. While the positional alignment of floors does not affect the topology, it is still important to properly align the floor plans one above the other, to enable proper 3D visualization of geometry. The alignment can be automated if floor plans contain a common reference feature (outer perimeter, reference point, etc.). There are two options from the coordinate system perspective. We can use a local coordinate system for each building, or we can choose to digitize all layers in a common national or global coordinate system, as we did. If the local coordinate system is chosen, we need to establish a link to a national or global coordinate system. This can be a point with national or global coordinates of the local coordinate system origin. Here it has to be mentioned that the IndoorGML standard supports the conversion of coordinate reference systems via anchor node element.

4.2. Transformation phase

In the second phase, the data from the first phase goes through a set of transformation processes (Fig. 7). All layers of the same type, digitized separately for each floor, are first merged into one layer, followed by three different sets of transformations, one set for each feature type (polygon, line, point). Additionally, the options for 2D and 3D data storage are presented within this phase. At the end of this subsection, we present the option for 3D visualization of the data, which can be used to perform quality checks and for a clear representation of the modelled data.

The polygons representing outlines of the rooms are transformed into 3D cells with a process of extrusion using the height attributes. Each digitized 2D polygon, representing a room outline, is “lifted” to the floor height and then extruded to ceiling height, which forms a closed 3D cell. After extrusion, the orientation of faces has to be checked and then the cell can be assembled into solid geometry. The final phase of the transformation of polygons is creating IndoorGML specific attributes (Fig. 8). A unique id is assigned to each cell using a global counter. When generating the models separately (at a different time or as separate processes) the uniqueness of cell ids should be ensured by saving the last used id, using unique ids within the model combined with the building's unique id, etc. The parent property and parent id attributes are static and contain information about the position and role in the hierarchy of the IndoorGML document. According to the concept of *Poincaré duality,* the cell and the corresponding node are connected. This connection is materialized with a duality *xlink:href* attribute. If we use the same numbering of cells and nodes (to obtain unique ids), only the node prefix has to be added to the numbering of cells to obtain a duality *xlink:href* attribute (“N1” for the node that corresponds to the “C1” cell).

The height values needed to position the nodes inside the linked cells in 3D space can be derived from the corresponding polygons. For implementation, we chose the mean value between the floor and ceiling height. The same types of attributes are added to nodes as to cells, with an additional connects *xlink:href* attribute that contains a list of all edges that are connected to a given node. This list was not included in the digitization phase, as the node can have any number of connected edges, so the connection information cannot be stored in the attribute table of nodes. Having the information about the start and end node for each edge acquired in the digitization phase, the list of all connected lines to each node can be created by joining the edge and node table. We implemented the list of connected edges by leveraging the list attribute option in FME Desktop software.

The edges are more challenging to put in the 3D environment than the nodes. The start and end height can be derived from node heights. As long as the connection between nodes is placed on a single level these heights are sufficient. When the two connected nodes lie on separate levels, the edge should change the height along its way.

Our solution simplified this problem using the start node height until the last line break and then changing the height to the end node height. This reduces the need for additional data input but can yield non-representative edges. Unique id, parent property and parent id attributes were also added to edges. We left out the duality *xlink:href* attributes used to link the edges and faces, as we do not provide modelling of cell connection surfaces (doors, windows) within our framework. If they exist in input data, they can be additionally included in the framework as a fourth digitization layer, transformed and written into the IndoorGML document as CellSpaceBoundary. The connects *xlink:href* attribute is sourced from the digitized line layer. The weight attribute determines the movement difficulty along the edge and represents key information in optimal path planning. The edge length and height difference can be used to automatically estimate the weight values, as they are available within the framework. However, more accurate values can be set if additional information or manual input is provided.

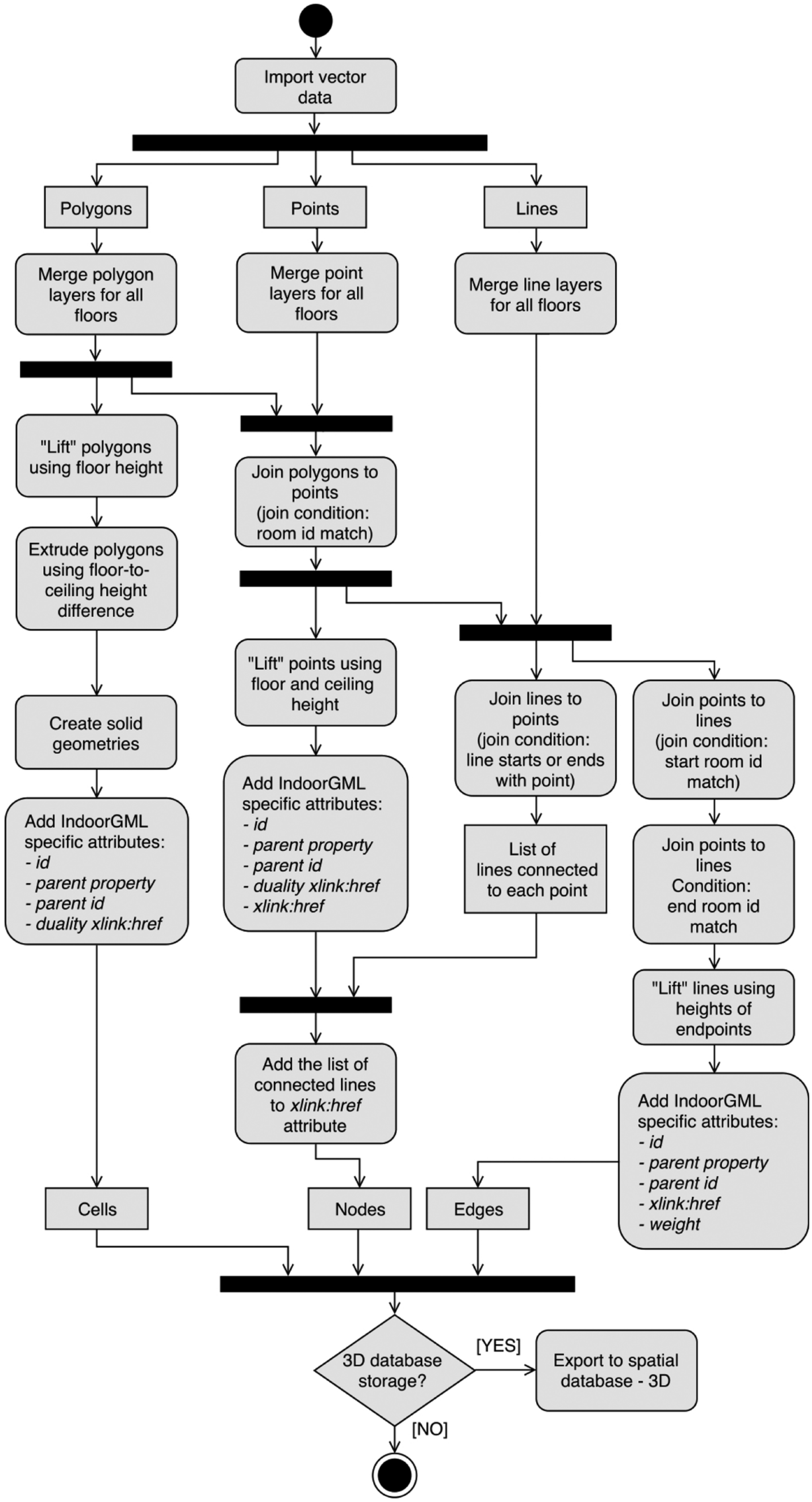

Fig. 7. UML activity diagram for the transformation phase of the proposed framework.

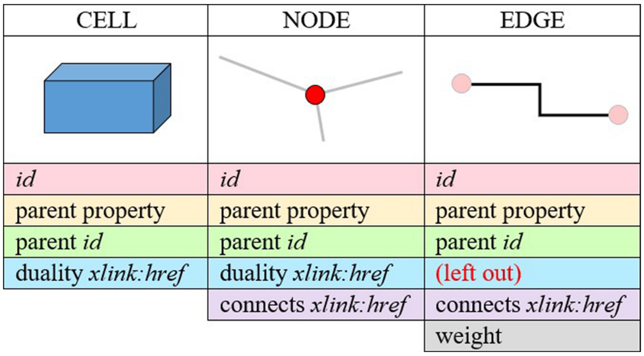

Fig. 8. IndoorGML specific attributes for each feature type (Tekavec and Lisec, 2018).

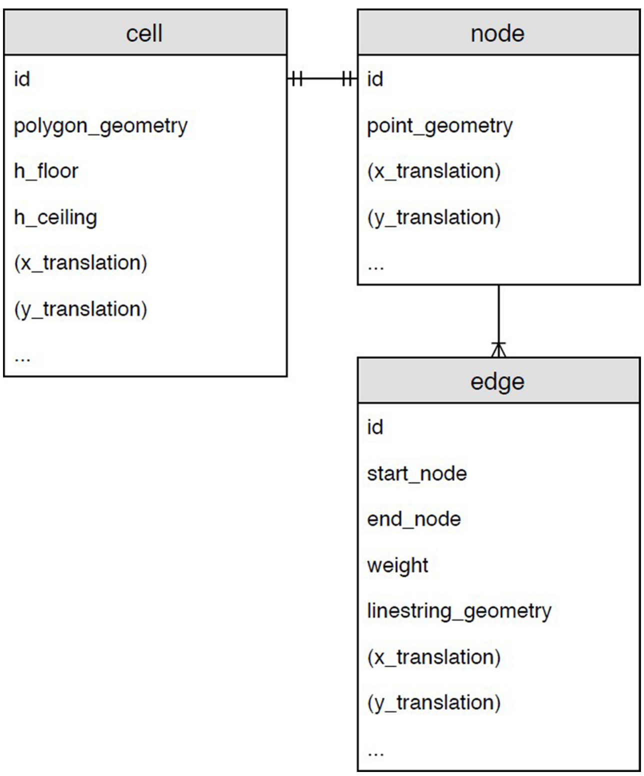

Fig. 9. The basic concept of 2D database storage.

4.2.1. Database data storage

The storage of the data in a database has many advantages compared to file-based data storage, especially from a data management and data dissemination perspective. Since the result of the proposed framework is in a file format, we propose two options of intermediate database data storage within the transformation phase. The storage is designed to enable fully automated creation of IndoorGML files. It can be seen as a breakpoint in the framework, from where the processes can be used only on request and data sourced from the database. The difference between options is the dimension of the stored geometries.

4.2.1.1. 2D database storage. Most of the databases support storing and management geometry following ISO SQL/MM-Part 3 (ISO, 2016) or OGC Simple Feature Access (OGC, 2010). They mostly support storage of geometry in the 3D space, but the functions for data management

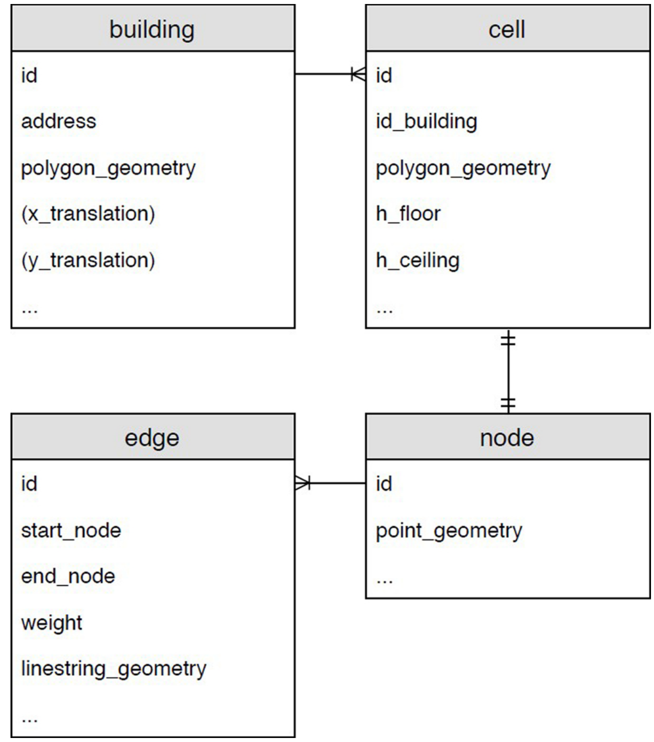

Fig. 10. 2D database storage with building table.

and analyses consider only two dimensions, with a few exceptions of some basic functions supporting 3D properties, e.g. Z-coordinate value retrieval. The 2D data storage can be performed right after the start of the transformation phase, as can be seen from the UML activity diagram for the data transformation phase (Fig. 7). Another option is storing the combined layers from the transformation phase. The stored geometries and attributes can be accessed and visualized by various GIS software, web services, etc. The basic concept of 2D database storage contains the

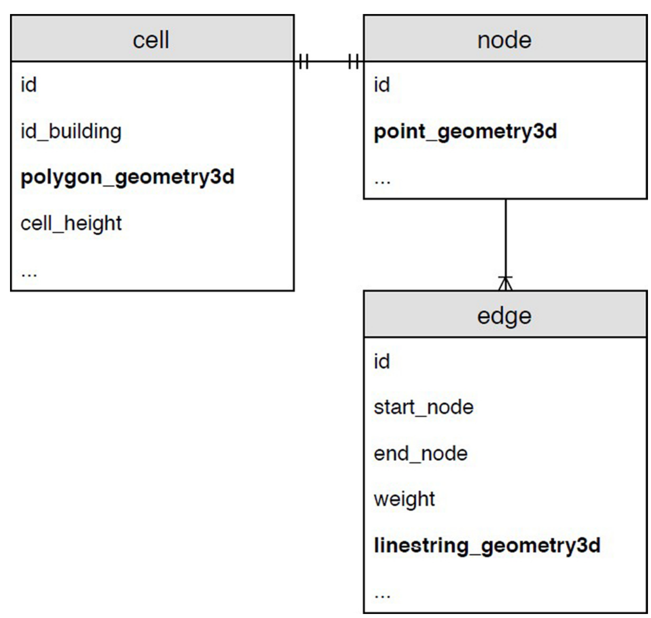

Fig. 11. The first level of 3D database storage.

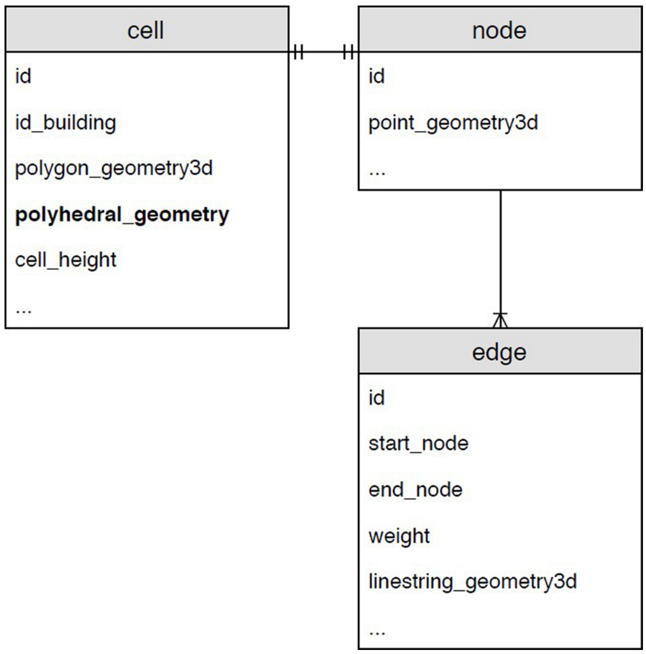

Fig. 12. Second level of 3D database storage.

cell, node and edge table (Fig. 9). Since the cells and nodes are related according to the Poincaré duality, the storage can be further simplified to store only the cell and edge table. In that case, node geometry and attributes would have to be derived from the cell table.

The brackets for x_translation and y_translation attributes indicate that these attributes are needed only when local coordinates are used. Instead, another point geometry column can be added. However, this can cause problems with some software that supports retrieval of only one geometry column per table. The "…" sign means that additional custom attributes can be added for each entity. By adding the building table (Fig. 10) related to official registers the data can be linked to address numbers and other data. The translation attributes if using local coordinates can also be stored in the building table. The rotation attribute can also be included but should be additionally accompanied by the rotation origin point. The 2D data storage is designed to allow fully automatic derivation of IndoorGML files, but not without additional processing.

4.2.1.2. 3D database storage. As mentioned in the previous section, most databases support storage of geometries in 3D space, including point, line string and polygon geometries. Some of the most advanced databases (Oracle Spatial, PostgreSQL with PostGIS) nowadays support storage of volumetric 3D geometries. Therefore, two levels of 3D database storage can be performed within the transformation phase.

The first level of 3D database storage can be performed when points, line strings and polygons are "lifted" onto the appropriate heights (Fig. 11). For cells, only one height attribute is now required for later extrusion. Also, the "lifting" of points and line strings with the polygon heights is not needed every time when deriving IndoorGML file out of the stored data. These geometries are also supported by most GIS software, web services, etc.

The second level of 3D database storage requires the support for volumetric 3D geometries. The open-source PostgreSQL database with PostGIS SFCGAL extension that offers state-of-the-art support for 3D geometries was chosen for our implementation. It can be performed after "lifting" of all features and extrusion of polygons into 3D solids. For nodes and edges, the storage is the same as in the first level, while cells are now stored as polyhedral surfaces, representing the outer shell of the solids (Fig. 12). To overcome the lack of current 3D support in GIS software, we propose a hybrid database storage, where "lifted" polygon geometry and cell relative height are still stored for cells.

4.2.2. 3D data visualization

Cells, nodes and edges modelled in 3D space open the possibility for their 3D visualization. The purpose of data visualization is often narrowed down to just being a tool for user-friendly and clear data presentation, but it is also an excellent tool to check data for inconsistencies and errors. Within our framework implementation, we used FME Inspector to inspect the results of each process of the transformation phase, as well as the end result – IndoorGML file. FME Inspector also allows visualization of the digitized layers and data stored in the database. To make the visualization of the data within the framework open and accessible, we propose the WebGL-based data visualization plugin for QGIS named Qgis2threejs. It takes 2D layers in QGIS and puts them in 3D space using height attributes (Fig. 13). The prepared visualization can be easily published to the web and opened in a web browser. We can further take advantage of QGIS advanced symbology capabilities to make data visualization as clear and descriptive as possible. The visualization has built-in commands for controlling 3D view, switching the layers on and off, adjusting transparency for each layer, and attribute-based labelling and access to feature attributes by their selection. Several studies deal with the challenges of 3D spatial data visualizations, such as occlusions, etc. (Shojaei, 2014; Wang, 2015; Zhou et al., 2015).

From version 3.0 on, QGIS has a built-in 3D viewer that has functionalities to visualize the spatial data in 3D. Currently, the 3D viewer does not provide sufficient functionalities to visualize volumetric objects representing indoor spaces, together with the connectivity graph. Also, the visualization is limited to QGIS software and cannot be disseminated online like the output of the Qgis2threejs plugin.

4.3. Structuration phase

In the final step, the transformed data is structured according to the IndoorGML structure and written into the IndoorGML document (Fig. 14).

The 3D cell solid geometry is assigned to a CellSpace element, node geometry to a State element and edge geometry to a Transition element. All geometries are encoded in GML (ISO, 2007). The parent id and parent property attributes enable the creation of *cellSpaceMember, stateMember* and *transitionMember* elements and their proper placement in the element hierarchy. The *duality* elements for CellSpace and State elements that establish links between them are created using duality *xlink:href* attributes. The *connects* elements for State and Transition elements are created with connects *xlink:href* attributes. These attributes contain a list of connected feature identifiers, solving the cardinality of the node – edge relation. The Transition element also get a weight element with a weight attribute assigned. All other IndoorGML elements and their attributes are created to comply with IndoorGML standard (Tekavec and Lisec, 2018).

```xml
<indoor:IndoorFeatures
     <indoor:primalSpaceFeatures>
          <indoor:PrimalSpaceFeatures gml:id="PS1">
               <indoor:cellSpaceMember>
                    <indoor:CellSpace gml:id="C1">
                         <indoor:Geometry3D>
                              GML Solid Geometry
                         </indoor:Geometry3D>
                         <indoor:duality xlink:href="#R1"/>
                    </indoor:CellSpace>
               </indoor:cellSpaceMember>
               …
          </indoor:PrimalSpaceFeatures>
     </indoor:primalSpaceFeatures>
     <indoor:MultiLayeredGraph gml:id="MG1">
          <indoor:spaceLayers gml:id="SL1">
               <indoor:spaceLayerMember>
                    <indoor:SpaceLayer gml:id="IS1">
                         <indoor:nodes gml:id="N1">
                              <indoor:stateMember>
                                   <indoor:State gml:id="R1">
                                        <indoor:duality xlink:href="#C1"/>
                                        <indoor:connects xlink:href="#T1"/>
                                        <indoor:geometry>


                                             GML LineString Geometry
                                        </indoor:geometry>
                                   </indoor:State>
                              </indoor:stateMember>
                              …
                         </indoor:nodes>
                         <indoor:edges gml:id="E1">
                              <indoor:transitionMember>
                                   <indoor:Transition gml:id="T1">
                                        <indoor:weight>1</indoor:weight>
                                        <indoor:connects xlink:href="#R1"/>
                                        <indoor:connects xlink:href="#R2"/>
                                        <indoor:geometry>
                                             GML Point Geometry
                                        </indoor:geometry>
                                   </indoor:Transition>
                              </indoor:transitionMember>
                              …
                         </indoor:edges>
                    </indoor:SpaceLayer>
               </indoor:spaceLayerMember>
          </indoor:spaceLayers>
     </indoor:MultiLayeredGraph>
</indoor:IndoorFeatures>
```

5. Discussion

Our framework was implemented using QGIS open source GIS software in the digitization phase, in which raster floor plans were digitized. For ensuing processes, we used the ETL software FME from SAFE software that supports 3D geometries and reading and writing IndoorGML files. For the input data, the raster floor plans from the Slovenian Building Cadastre were selected.

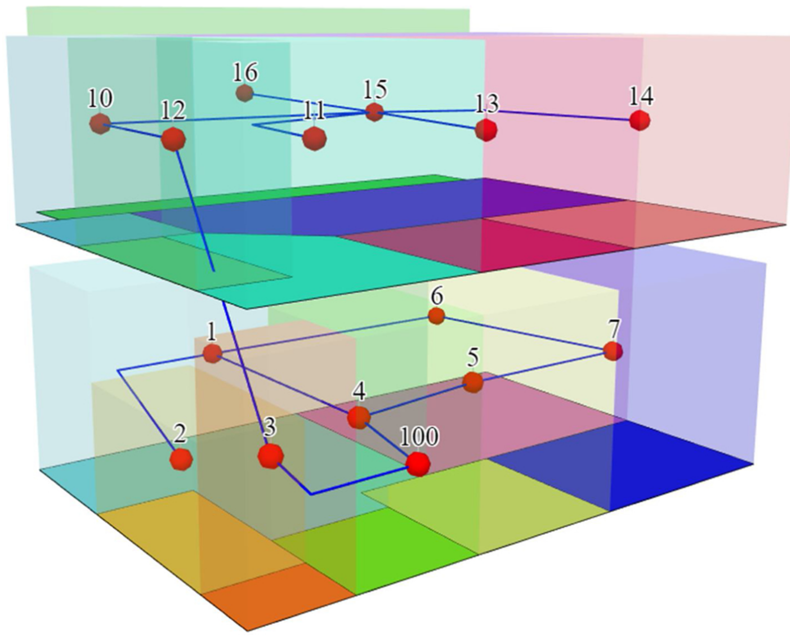

Fig. 13. 3D visualization of the transformed data (Tekavec and Lisec, 2018).

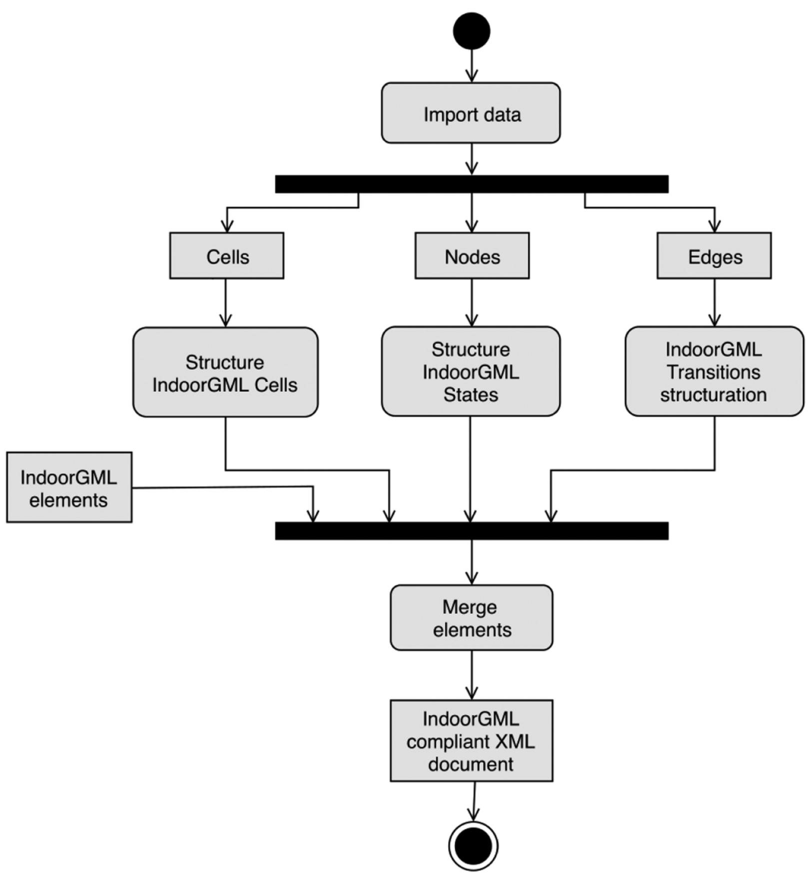

Fig. 14. UML activity diagram for the structuration phase of the proposed framework.

5.1. Data assessment

The presented framework can be used as a tool to identify the advantages and disadvantages of the (cadastral) data suitability for 3D indoor modelling. This is important the organizations, such as cadastral authorities that are responsible for the cadastral data, to devise the required changes in the data model if they decide to support 3D indoor modelling.

For the selected case, the Slovenian Building Cadastre, many advantages were identified in a very early stage of our research and were the reason why we considered using it for 3D indoor modelling. The data is centrally stored and maintained which makes it easily

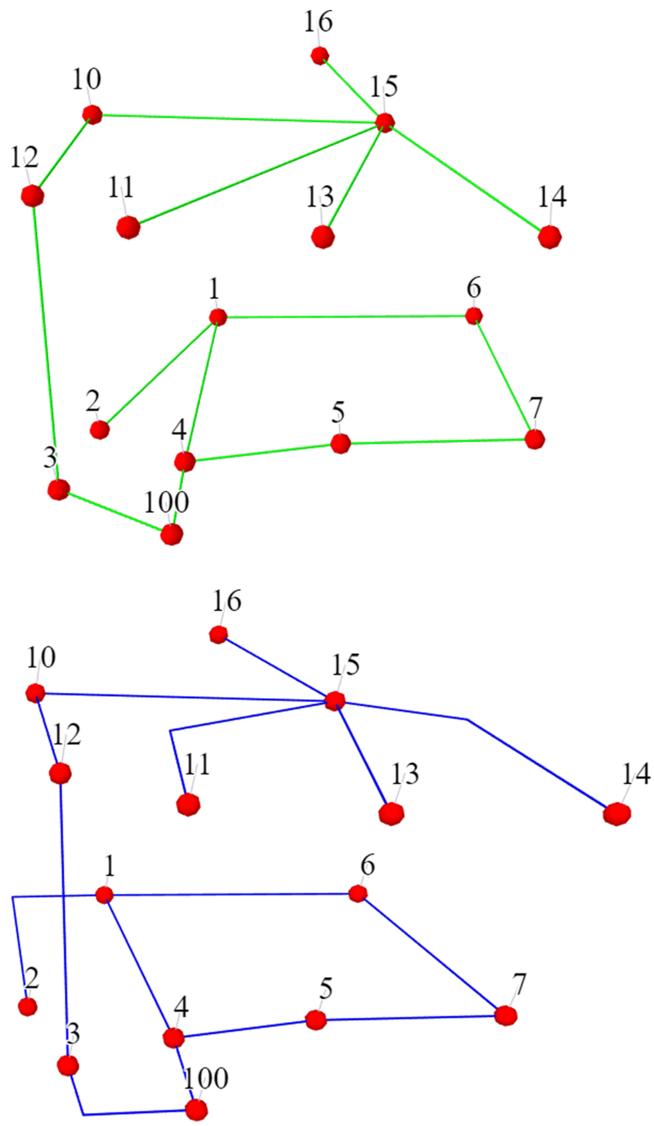

Fig. 15. Automatically derived graph from room polygons and room connection information (top) and graph containing digitized nodes and edges (bottom) (Tekavec and Lisec, 2018).

accessible, provided one has the access rights (attribute data is public, documentation is available to authorized land surveyors). In this aspect, the cadastral data is more useful than construction data, which is often hard to get access to and is not centrally stored. Another important advantage of cadastral data, compared to construction plans or data provided within BIM, is that the cadastre provides as-built data, while construction data often provides only as-planned information that can significantly differ from as-built data. As the Slovenian Building Cadastre provides a technical basis for condominium registration, the 3D indoor models derived from the cadastral floor plans can be directly linked to the established rights, restrictions and responsibilities in the building. The 3D model can be further linked to the Register of house numbers, allowing integration of indoor and outdoor navigation. In 2018, the Slovenian Building Cadastre introduced submission of floor plans in vector format together with floor heights which significantly reduces the manual input in the digitization phase of the proposed framework.

The disadvantages mostly originate from the fact that the data model for the Slovenian Building Cadastre was not designed to support 3D modelling and indoor graph derivation. Until 2018, the floor plans were submitted in raster format, requiring initial digitization. As already stated, since 2018, the floor plans are submitted in a vector format but are strictly limited to outlines of building parts, without the possibility to include room geometries. This significantly limits the usability of the floor plans for 3D indoor modelling. The paper focuses on using the building floor plans, which are not available for most of the buildings in Slovenia, as the full building registration is mandatory only since 2006. This is a significant limitation due to the fact that the proposed framework is not allowing a nationwide 3D indoor modelling.

5.2. Findings

The detailed description of processes needed to develop a 3D indoor model of a building based on cadastral data resulting in an IndoorGML document opens up several topics for discussion.

In the final IndoorGML document, we decided to use the 3D geometry of the cells. The only method to obtain 3D geometries that includes a reasonable amount of additional manual input is the extrusion of 2D polygons using floor and ceiling heights. While it is the most feasible approach, it also doesn't bring many advantages over 2D geometries. 3D geometries enable more realistic visualizations but have limitations, such as occlusions, that should be considered, like occlusions. The additional heights can be useful to determine if the height of the space enables navigation through it (some spaces can have very low ceiling). If the navigation graph is placed in 3D space, we can determine the height difference of the calculated route and thus get additional information about how demanding it is, as locomotion in a vertical direction is more demanding.

For the Slovenian case study, it has been shown that in the first part of the framework several missing data have to be added manually. Additional data are generally not cheap, and its acquisition is time-consuming, especially for the indoor environment. As already mentioned, progress has been made by introducing the floor heights and vector floor plans in the Slovenian Building Cadastre in 2018.

The inclusion of the information about which rooms are connected into the cadastral documentation would be a greater challenge, as it is far beyond the scope of the current land administration system. On the other hand, not much additional information would need to be collected and stored in the cadastral database. A basic connectivity graph without a detailed edge geometry could already be generated from room connections in tabular form. The nodes can be created automatically as centroids and then also edges, using the geometry of nodes and connectivity information from the table. Each edge is therefore constructed as a straight line using start and end node geometries. The algorithms for automatic generation of centroids can fail to place the centroid inside the polygon feature, but that can be automatically checked and manually corrected. Generated in such a way, a graph would have weak geometric properties, but its topology would be valid. Teo and Yu (2017) construct the connectivity graph the same way from IFC data and propose manual editing of the edges for complex and open spaces. Fig. 15 shows a comparison of an automatically generated graph from tabular room connectivity data and a graph generated with the digitization of nodes and edges. However, it should be emphasized that with increased building complexity, the difference between the two graphs would also increase.

To reduce the need for additional manual input, we considered only IndoorGML core module. However, the model can be semantically enriched with IndoorGML Indoor Navigation module that provides information, useful for indoor navigation applications, by classifying the core module elements into navigable and non-navigable ones. If the local coordinates are used for modelling, the anchor space element can be used to establish a link between local and global coordinate reference systems and thus enable the integration of indoor-outdoor navigation.

The IndoorGML standard provides two different approaches for cell modelling, a "thin wall" model and a "thick wall" model. We have chosen the "thin wall" model, as it is closely aligned with floor plans in

Table 1
Comparison between JInedit solution and our proposed framework.

	JInedit	The proposed approach
Implementation software	standalone software	various possibilities
Floor heights	one for each floor	one for each room
Additional data inclusion	not possible	possible
Export to other formats	not possible	possible
Database integration	not possible	possible
Required user skills	low	high

the Slovenian Building Cadastre, which does not account for the thickness of walls. If construction plans are used instead, it would be better to use the "thick wall" model, as there, the walls are drawn with their actual thickness. One of the drawbacks of the "thin wall" model is that it does not allow creating the cells with the correct geometry while maintaining the correct outer shape of the building. These two concepts also raise open questions regarding modelling rules for 3D geometries in a 3D real property cadastre. If the 3D geometry provides the only reference to the physical structures of the building, which define the real extent of RRR in space, the correct geometry is not as important as in the case when 3D geometry defines the exact extent of RRR. The second option allows the reconstruction of the property unit geometry without the building structure (not yet built or demolished). An open (legal) question is also how the border between two property units is defined, the middle of the wall or on each side of the wall (Atazadeh et al., 2016).

The proposed framework has several features in common with JInedit software (Seo, 2017), which is an open source software that enables the creation of IndoorGML documents based on raster floor plans. While it uses the same input and provides practically the same output, there are several differences between our approach and Jlnedit software (Table 1):

- The JInedit is standalone software, while the process presented in this paper is a set of software independent operations that can be implemented using various spatially enabled software, which requires more skilled users.
- The proposed process enables more flexible height provision (each room can have its own floor and ceiling height) and hence better representation of a real-world situation.
- Only limited data can be acquired in Jlnedit, while the proposed process allows additional data, such as rights, restrictions and responsibilities, currently not supported by the IndoorGML standard to be captured and stored in the spatial database.
- The proposed process enables the export of 3D geometry in various 3D formats.
- The proposed process allows direct storage of geometry and attributes from the transformation phase into the database where routing capabilities can later be used.

6. Conclusions

The study aimed to create a framework for 3D indoor modelling of buildings from input raster floor plans to an IndoorGML compliant document. A detailed workflow for 3D indoor modelling has been provided, comprising a chain of processes starting from initial cadastral data in the form of a raster floor plan and ending with the OGC IndoorGML compliant document. We have tried to design the whole workflow in a generic way as much as possible, while also considering the particularities of Slovenian cadastral data. The IndoorGML standard is used for final outputs aiming to provide a model suitable for indoor navigation and location-based services. The data stored in the database enables fully automatic IndoorGML document generation on request while also taking advantage of all functionalities of a spatial database. The proposed approach is software independent and can be implemented with various spatially enabled software packages.

For the Slovenian case study, we identified key missing data in the current documentation of the Building Cadastre that is needed for 3D indoor modelling. To produce proper results, the need for vector floor plans has been identified, and additionally, floor height information and room-to-room connectivity are currently missing in the cadastral database. Although the paper does not focus on semantic enrichment of a 3D model, it should be stressed that additional data can be provided by linking the source data to land administration databases, which has great potential for semantic enrichment of IndoorGML models with information about rights restrictions and responsibilities, the value of the real estate, house number etc.

Although the framework is developed based on raster floor plans from Slovenian Building cadastre, it can be used for any similar data that represents 2D floor plans with some adjustments, especially regarding the manual input. A detailed description of all processes and the process diagram, together with the following remarks and considerations, can serve as a starting point to assess the data in national land administration systems worldwide, whether and to what degree the data can be used for 3D indoor modelling and what should be changed. Future research will be focused on the analysis of other data which is available by linking the source data to connected databases and their usability in the context of indoor navigation applications.

Acknowledgements

The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0406 Earth observation and geoinformatics).

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Tekavec, J., Lisec, A., Rodrigues, E. (2020)

ISPRS International Journal of Geo-Information, 9(10), 598

DOI: 10.3390/ijgi9100598

Faktor vpliva za leto 2019: 2,239 (Q3)

International Journal of
Geo-Information

Article

Simulating Large-Scale 3D Cadastral Dataset Using Procedural Modelling

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Received: 1 September 2020; Accepted: 8 October 2020; Published: 11 October 2020

Abstract: Geospatial data and information within contemporary land administration systems are fundamental to manage the territory adequately. 3D land administration systems, often addressed as 3D cadastre, promise several benefits, particularly in managing today's complex built environment, but these are currently still non-existent in their full capacity. The development of any complex information and administration system, such as a land administration system, is time-consuming and costly, particularly during the phase of evaluation and testing. In this regard, the process of implementing such systems may benefit from using synthetic data. In this study, the method for simulating the 3D cadastral dataset is presented and discussed. The dataset is generated using a procedural modelling method, referenced to real cadastral data for the Slovenian territory and stored in a spatial database management system (DBMS) that supports storage of 3D spatial data. Spatial queries, related to 3D cadastral data management, are used to evaluate the database performance and storage characteristics, and 3D visualisation options. The results of the study show that the method is feasible for the simulation of large-scale 3D cadastral datasets. Using the developed spatial queries and their performance analysis, we demonstrate the importance of the simulated dataset for developing efficient 3D cadastral data management processes.

Keywords: building models; 3D cadastral system; procedural modelling; SQL; 3D visualisation

1. Introduction

As the built environment is increasingly becoming spatially complex, land administration systems (e.g., cadastral systems) are challenged by an unprecedented demand to support decisions in utilising space above and below the earth's surface [1]. Consequently, cadastral systems tend to be very complex information systems that require the efficient organisation of data to support their management. Additionally, a cadastral system is usually developed for a whole jurisdiction (e.g., a county or a country) which requires handling of a large amount of data. With the introduction of 3D geospatial models representing 3D real property units in the so-called 3D cadastre or 3D land administration system, this has become a very challenging task [2,3]. The development of 3D cadastre has been the subject of intensive research activity in the past two decades. Generally, the research has been focused on three main aspects of a 3D cadastre: the legal, the institutional and the technical. The legal aspects of 3D cadastre have been studied by Paulsson [4]. The study provides an international overview of legal systems and the analysis of several forms of 3D property rights. Kitsakis and Dimopoulou [5] studied and compared the establishment of multi-surface property in Common and Civil law jurisdictions. Paulsson and Paasch [6] analysed the research on the legal aspects and emphasised the need for additional research in this field. The institutional aspects of 3D cadastres are mainly studied within the research, concerning the developments in specific countries [7–11]. Ho et al. [12] studied the institutional factors in the development of 3D cadastral systems. Stoter [13] provided a comprehensive study of the 3D cadastral topics, with the focus on the technical aspects. Several options for realisation of 3D cadastral systems were investigated, including DBMS data storage and maintenance. The DBMS storage and management of 3D spatial data has been studied in [14–16] and its validation in [17–19]. The research in the field of 3D cadastre has also been related to the challenges for the visualisation of 3D cadastral data [20,21]. Regarding 3D cadastral data modelling, several data models have been studied and proposed. Aien et al. [22] provide an assessment and comparison of the existing data models for 3D cadastre applications. The authors conclude that none of the discussed models, including the conceptual model provided within the international standard ISO 19152:2012 on the Land Administration Domain Model (LADM) [23], fully supports 3D data modelling. Another study, focusing on linking physical space with legal boundaries, has been conducted by Rajabifard et al. [24] for the case of the jurisdiction of Victoria, Australia. The authors discuss Open Geospatial Consortium standards, namely CityGML [25], IndoorGML [26], and LandInfra [27], and their integration with LADM, together with the 3D cadastral data model (3DCDM), which was designed to support both 3D legal objects and their physical counterparts [28]. According to Kalogianni et al. [1], there is currently no country with a fully operational 3D cadastral system. The authors emphasise that some jurisdictions already support some aspects of 3D cadastre, but this is mainly a part of pilot projects and prototypes (see [29–31]). Consequentially, this means that no real large-scale 3D cadastral datasets are available, except for some individual cases that were the subject of existing studies.

While advancements in remote sensing technology enable us to obtain large-scale models of building exteriors [32], this is not enough for cadastral use in case of buildings, as some degree of indoor spatial information is needed for unambiguous delineation of a building into real property units, to which rights, restrictions, and responsibilities refer. Indoor spatial data acquisition and modelling is challenging and requires an individual approach for each building [33]. Studies regarding this issue have also been done related to a 3D cadastre. Kitsakis and Dimopoulou [34] investigate the usability of existing cadastral documentation for 3D modelling. Vučić et al. [8] focus on the Croatian land administration system and investigate the possibilities of upgrading the cadastral system to 3D by linking topographic data. Tekavec and Lisec [35] provide a framework for 3D indoor modelling based on existing cadastral data. All studies deal with a limited number of individual buildings. Consequently, their usability in obtaining a large-scale dataset is limited. To overcome this issue, it is hypothesised that the 3D cadastral system development can benefit from using a synthetic dataset that simulates some aspects of the real data.

In this paper, the method that uses procedural modelling for simulating the synthetic 3D cadastral dataset is developed and discussed. The research is limited to buildings, as they represent the dominant feature in the field of geospatial data modelling within a 3D cadastre. Using the existing cadastral data for the study area, we aimed to obtain a more representative placement and configuration of the simulated buildings. A similar approach, without procedural modelling, was proposed by Ledoux and Meijers [36] and Biljecki et al. [37] aiming to generate 3D city models based on 2D footprints and attribute data. Procedural modelling methods are rooted in computer graphics and refer to several techniques to create 3D models and textures from sets of predefined rules, combined with randomising some of the parameters. We focus on methods that generate whole buildings from indoor space arrangements. In this context, the study of Watson et al. [38] has to be mentioned, who reviewed the applications of procedural modelling in computer graphics. Merrell et al. [39] focus on the automated generation of building layouts based on a Bayesian network trained on real-world data. Smelik et al. [40] provide a survey of the methods for procedural modelling of virtual worlds. Camozzato [41] classifies the approaches to subdivision algorithms [42], tile placement algorithms [43], inside out algorithms [39] and growth-based algorithms [44]. Another classification of automatic approaches for indoor layout generation is provided by Rodrigues et al. [45]. The focus is on the architectural domain, where procedural modelling is divided into area assignment, area partitioning, space allocation, hierarchical construction, conceptual exploration and design adaptation. Procedural modelling is also used in the geoinformation domain. Gröger and Plümer [46] generated building indoor models to derive route graphs. Zhu et al. [47] used procedural modelling to generate virtual scenes. Based on the work of Tsiliakou et al. [48], Kitsakis et al. [49] used ESRI CityEngine to produce 3D building models of a traditional village. CityEngine procedural capabilities have also been studied by Ribeiro et al. [50] to test 3D visualisation of 3D cadastral data and by Neuenschwander et al. [51] to generate and visualise green space patterns in a 3D environment. Biljecki et al. [52] used the procedural modelling approach to simulate the CityGML datasets, which were used to analyse different variants of LODs (level of detail) and their influence on the performance of spatial analyses. The procedural modelling engine Random3DCity was used by Kumar et al. [53] to generate artificial TIN terrain models at different LODs in CityGML format.

In the following chapter, we present the developed approach for simulating the real 3D cadastral dataset by generating a synthetic dataset using a Hybrid Evolution Strategy [54] as a procedural modelling method to create buildings with different geometries and functional programs. The generated buildings are linked to the Slovenian cadastral data. The simulated dataset was stored in a spatial database management system (DBMS), where we illustrate the performance testing for some 3D spatial queries related to data consistency and we evaluate options for 3D visualisation.

2. Materials and Methods

Our study combines reality-based and procedural building modelling. Namely, the simulation of the cadastral dataset is based on available data about existing buildings, acquired from the official records at the National Surveying and Mapping Authority, combined with the simulated data generated by procedural modelling, where randomised 3D building models are constructed based on the predefined rules. The developed approach aims to satisfy the following requirements: (i) the process of generation of the synthetic dataset is guided by the existing cadastral data from the current cadastral database; (ii) the 3D building models in the dataset should be randomised; and (iii) the dataset should be stored in a spatial DBMS, where data storage, access, maintenance, and manipulations can be performed and evaluated. Using the existing cadastral data for the study area, we have tried to obtain more representative placement and configuration of the simulated buildings, where we focus on residential buildings. Figure 1 summarises the framework of our study. The process starts by defining the type of residential units. This information is then used for generating the synthetic dataset using the procedural modelling method [54]. The generated models are then transformed to fit into a GIS environment to be suitable for data storage in the spatial DBMS. The procedurally generated 3D building models are then linked to real cadastral data on buildings by location and the number of storeys. In this study, spatial DBMS is created and run locally. Its structure is focused on the storage of the simulated 3D dataset in the form building models, including their interior spaces, i.e., rooms. Due to different legal frameworks, historical background and other factors, countries have various definitions of real property units as well as various implementations of cadastral databases. The stored simulated data are designed to allow linking data with additional country-specific data.

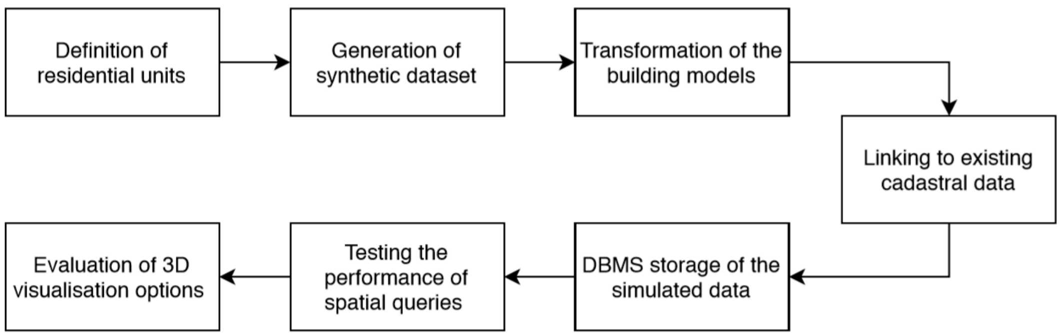

Figure 1. Study concept framework.

The study is generic with respect to procedural modelling of 3D building geometries and their transformations. The reality-based part of the study is related to the Slovenian cadastral data with its specific features [55]. For the case study, all residential buildings in Slovenia stored in the Slovenian building cadastre were used. Based on the simulated data, we evaluated the performance of several queries aimed at 3D cadastral database maintenance and data quality control.

2.1. Procedural Modelling of Buildings

For this study, the Evolutionary Program for the Space Allocation Problem (EPSAP) algorithm was used [54]. The EPSAP algorithm consists of a two-stage approach that has an Evolution Strategy (ES) framework, where the mutation operation is replaced by a Stochastic Hill Climbing (SHC) method. Figure 2 depicts the overall generation process. The algorithm starts by creating a set of candidate designs that have their rooms randomly dispersed in the 2D space on each storey. Then, each design is evaluated according to a weighted-sum cost function of eighteen penalty functions that are minimised. At this moment, the second stage starts by iteratively changing each design with random geometric and topologic transformations, such as translation, rotation, stretching, reflection, and swapping. If the transformed design produces an improved solution, the new design is preserved. When the SHC stage is incapable of finding further improvements, the second stage ends and the first stage resumes by selecting solutions that have a fitness lower than the average fitness of all designs. The worst solutions are replaced by new randomised ones, which are also evaluated. This cycle is then repeated until ES stage reaches a maximum number of iterations or is unable to find more improved design solutions (for the complete description of the EPSAP algorithm see [54]). Lastly, the whole 3D building is produced by adding height to each storey (measured from the storey floor to the ceiling), extruding rooms for one or more storeys (e.g., a stair serves a range of storeys), positioning the openings in relation to the room floor (i.e., the distance from the floor to the base of the opening) vertically, and giving height to the opening (i.e., the void height in the wall). In the case when a storey multiplier is present, the storey is repeated.

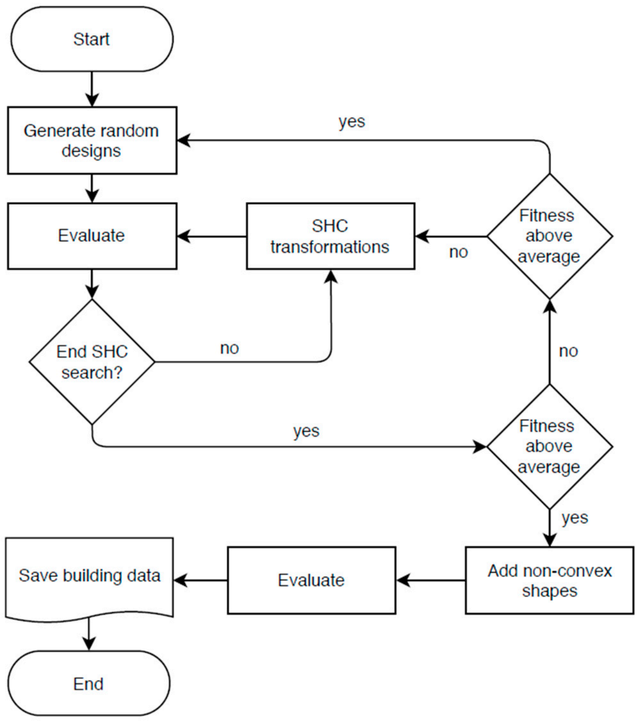

Figure 2. Evolutionary Program for the Space Allocation Problem (EPSAP) algorithm workflow (adapted from ref. [54]).

For our study, six residential building types (two types of detached houses, three types of multi-storey apartment buildings, and a single type of multi-storey apartment building with commerce on the ground floor) were generated. Two of the building types are detached single-family houses of one and two storeys, respectively. The single-storey house comprises bedrooms, bathrooms, living room, kitchen, corridor, and entrance hall. The two-storey buildings have an interior stair that separates the public part of the house from the bedrooms, which are located in the upper storey. Three of the building types are multi-storey apartment buildings of four storeys. These buildings are different in the number of apartments per floor and the number of bedrooms. The last type of building is an eight-storey building that has commerce spaces on the ground floor and access to the roof on the top floor. On the intermediate floors, two three-bedroom apartments are served by a stair and an elevator.

2.2. Transforming the Generated Building Models

The building models comprise enclosed volumes with surfaces for walls, floors, ceilings, doors, and windows (see Figure 3). The adjacent rooms are in a touching relationship, having common interior walls, slabs, and door surfaces.

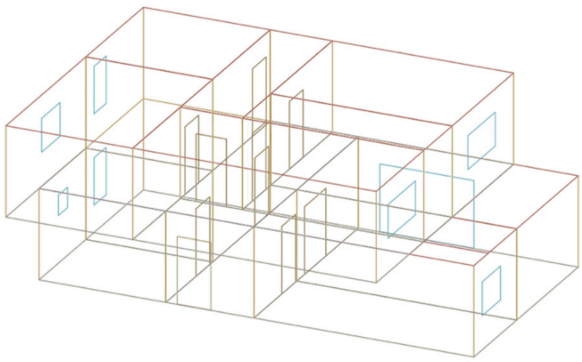

Figure 3. Simulated two-storey building model comprising of wall, door and window surfaces.

The data model of the simulated buildings can be linked to the LADM data model, as presented in Figure 4. The simulated models of buildings represent their physical components. It must be noted that the boundaries of real property units may not coincide with the physical features of a building [56]. However, in case of buildings, a strong link exists between physical and legal spaces, which has been studied by Aien et al. [28], Li et al. [57] and Knoth et al. [58]. These studies also include the links to the LADM standard data model that are similar to our study. In recent years, many studies investigated the potential of integrating building information models (BIM), which contains physical information on buildings, with 3D cadastre [59–61]. In this study, the real property units are realised by the aggregation of rooms that belong to the corresponding real property units. Therefore, the investigation is limited to physically defined 3D boundaries.

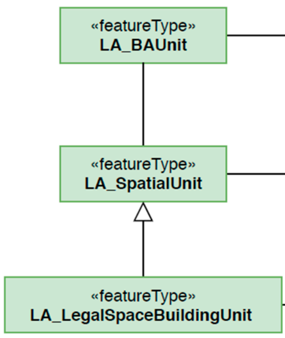

Figure 4. Linking Land Administration Domain Model (LADM) classes (green) to the data model of simulated buildings (white).

After their generation, the 3D building models are transformed into a data format that is suitable for storage in a spatial DBMS. First, each building needs an assignment of a unique identifier followed by the decomposition of the geometries into individual parts. The decomposed geometries enable the application of the filter that selects only surface type geometries. The selected surfaces are grouped by the room identifier, which enables the modelling of solid geometries for each room (see Figure 5).

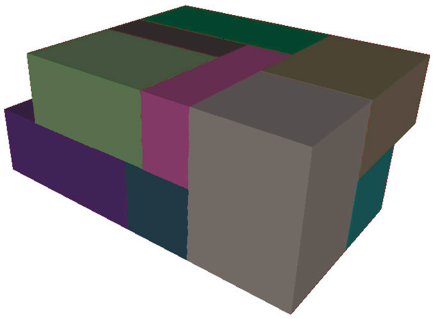

Figure 5. Solid geometries created from the predefined surfaces.

The generated 3D building models are placed in a local coordinate system but are not centrally placed. The placement of the models varies relative to coordinate origin, as shown in Figure 6a. Therefore, the central point is calculated for each generated 3D building, based on the room geometries. The Z coordinate of the central point is set to the minimum Z value of the bounding box. The room geometries are then moved using an offset vector connecting the local coordinate system origin and the calculated central point, as shown in Figure 6b.

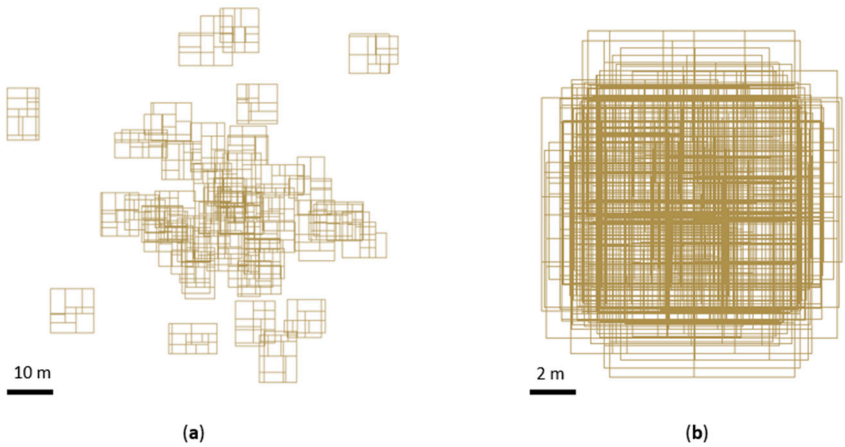

Figure 6. (**a**) Original placement of generated 3D building models; (**b**) the same models after their placement to the local coordinate system origin.

The 3D building geometries are then inserted in the PostgreSQL DBMS with PostGIS and SFCGAL extensions, which support 3D spatial data storage and maintenance. Before inserting 3D geometries, to avoid issues with geometry conversion from spatial ETL software (FME Desktop Software)-supported geometries to PostGIS, the geometries were triangulated.

Besides the building interior, a 3D model of the building exterior extents is derived from the generated 3D building models. A (buffered) 3D model of the building in the context of a 3D cadastre can also serve as a representation of a building legal space. First, the 2D outline has to be generated from room geometries. All surfaces of the building model need to be transformed into 2D surfaces. The vertical surfaces transform into line shape and thus need to be filtered out. Our approach has been to calculate 2D surface area and filter all surfaces having zero or very small area (computational error and rounding). The remaining 2D surfaces are dissolved into one 2D surface representing the building

2D outline (Figure 7). The 2D building outline can be buffered to enclose all room geometries. The 3D representation of the building is generated by extruding the 2D building outline. The extrusion vector is calculated from the vertical bounds of the room geometries. If we opt to use buffering, we can place the 2D outline below the minimum vertical bound of room geometries and extrude over the maximum vertical bound. The geometry of each 3D building exterior model should also be moved using the displacement between the central point and coordinate system origin and triangulated before being inserted into spatial DBMS.

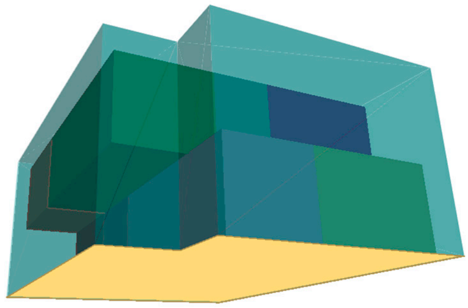

Figure 7. 3D room geometries (random colours), 2D building outline (yellow) and extruded 3D building exterior geometry (transparent blue).

In the spatial DBMS, two tables are created, one for storage of generated 3D models of rooms and one for 3D models of buildings (Figure 8). These two tables are linked by the common building model identifier (*id_bldg_gen*). The 3D geometries of rooms are stored as polyhedral surfaces, together with the unique room identifier (*id_room_gen*), the identifier of the corresponding building and optionally the number of the storey in which the room is located (*storey_number*). For the buildings, the 3D geometry is also stored as a polyhedral surface. Alongside geometry, the attributes containing the unique identifier of the building and the number of storeys are inserted. Optionally, the 2D geometries of rooms and buildings can be stored for applications, where only 2D geometries are needed or supported.

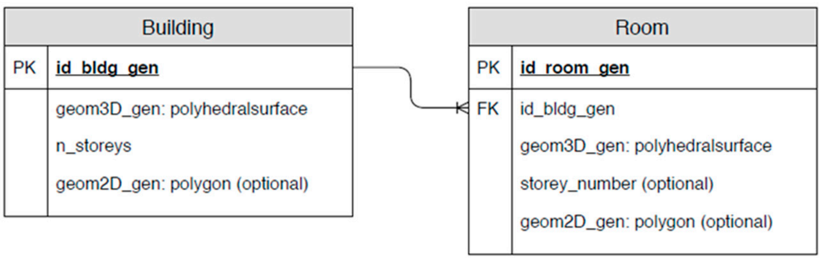

Figure 8. Database management system (DBMS) storage of the transformed procedurally generated 3D building models.

2.3. Georeferencing Using the Link to the Existing Cadastral Data

All the transformed building models are stored in the spatial DBMS in a local coordinate system. However, this is not close to the real case of 3D cadastral data. The generated building models need to be spatially referenced and randomised, as stated in the initial aims of this study. This part is based on the characteristics of Slovenian cadastral data on buildings—the Slovenian building cadastre. There, the buildings are stored in the form of a vector layer with building outline polygons and an attribute database. A common building identifier connects the two datasets. Models are georeferenced by two parameters to the real (Slovenian) data: (i) building location, defined in the national geodetic reference coordinate system D96/TM based on ETRS89; and (ii) the number of storeys. The building location is calculated from a centroid of a building polygon. Those centroids are considered as their reference centre in the local coordinate system origin.

The referencing is performed using SQL queries as all the data (real cadastral data and generated building models) are stored in the DBMS. For the simulated cadastral dataset, we have created two tables, first for data on the building interior (*room_simulated*) and second for the building exterior (*building_simulated*) (Figure 9). The two tables are connected by the cadastral building identifier (*id_building*). Using the *id_building*, the available cadastral attributes can be added optionally, for instance, the identifier of the parcel to which the building is related. For each building, the corresponding data on building interior (room geometries) is inserted into the *room_simulated* table. There, the identifier of the real property is stored, which is used to aggregate the rooms into real property units. Optionally, the storey number where the room is located can be stored. Various options for DBMS storage of similar data are discussed in [35].

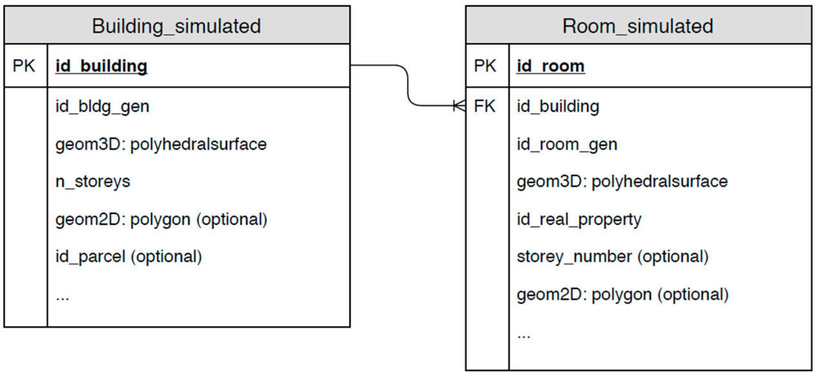

Figure 9. DBMS storage for the simulated 3D cadastral dataset.

Each building from real cadastral data (*id_building*) gets one procedurally generated 3D model assigned (*id_bldg_gen*), which is moved to the location of the building. There are various approaches to the selection of the corresponding procedurally generated model:

- Generate only one 3D model for each parameter: in our case, one model for each number of storeys. The same 3D model is selected for all buildings with the same number of storeys.
- Generate a given number of 3D models for each parameter (number of storeys). One of the 3D models is randomly selected and referenced to real cadastral data.
- Generate a random 3D model for each real building.

The first approach is the simplest and can be used in cases where the diversity of the models is not a key issue. SQL statements (Appendices A.1 and A.2) are used to select the data that are to be inserted into the *building_simulated* and *room_simulated* tables (the real cadastral data are stored in the table *cadastral_building*). In both SQL queries, the *ST_Translate* function is used to move the procedurally generated 3D geometries to the location of the building. The *ST_Translate* function parameters are the geometry and component of the displacement vector in the X, Y and Z directions. In the SQL queries, the *geom_c* attribute is a point geometry of the building centroid, and h is a building terrain height attribute. Referencing is performed with the join operation on the number of storeys (one model is available for each storey). The referencing of the rooms is similar to the first query, with the additional join of the *room* table.

If diversity of the models is required, the second and the third approach can be used. The second approach represents a balance between the first and the third approach, providing a flexible degree of randomness in the simulated dataset. Following the second option, we randomly select a corresponding model for each building. The SQL query that selects data for the *building_simulated* table is therefore modified to select a random model (Appendix A.3—modifications of Appendix A.1 in bold text). The join operation joins multiple models to each building, which are then grouped and randomly ordered. From each group, the first joined model is selected using row number. The SQL query that selects data for the *room_simulated* table is also modified (Appendix A.4—modifications of

Appendix A.2 in bold text). Instead of joining the *building* table, the *building_simulated* table is joined to the *cadastral_building* table. By doing this, we get information as to which model is assigned to the building. With this information, the *room* table can be joined.

3. Results

The Slovenian building cadastre classifies buildings based on their usage. In this study, we focus only on buildings that are classified as residential. The reason is that more complex building types such as schools and hospitals require more complex functional programs. They cause the exponential growth of the required computational time due to the combinatorial nature of the problem.

The buildings were generated in four runs, each for a building type, in a 2.8-GHz Dual-Core CPU with 8 GB of RAM. Multi-threading was used. In the generation of each building type, the duration of the processing time ranged from 49 min to 15 h, depending on the complexity of the building requirements. First, the number of storeys in the Slovenian building cadastre was investigated. The test showed that 94% of the residential buildings have four or fewer storeys. Based on this, we decided to use 1, 2, 4 and 8 storey building models for the case study. In total, nine algorithm runs were carried out, producing 282 building models. Figure 10 displays a few examples of the generated buildings (all generated buildings can be accessed from the link provided in the supplementary materials).

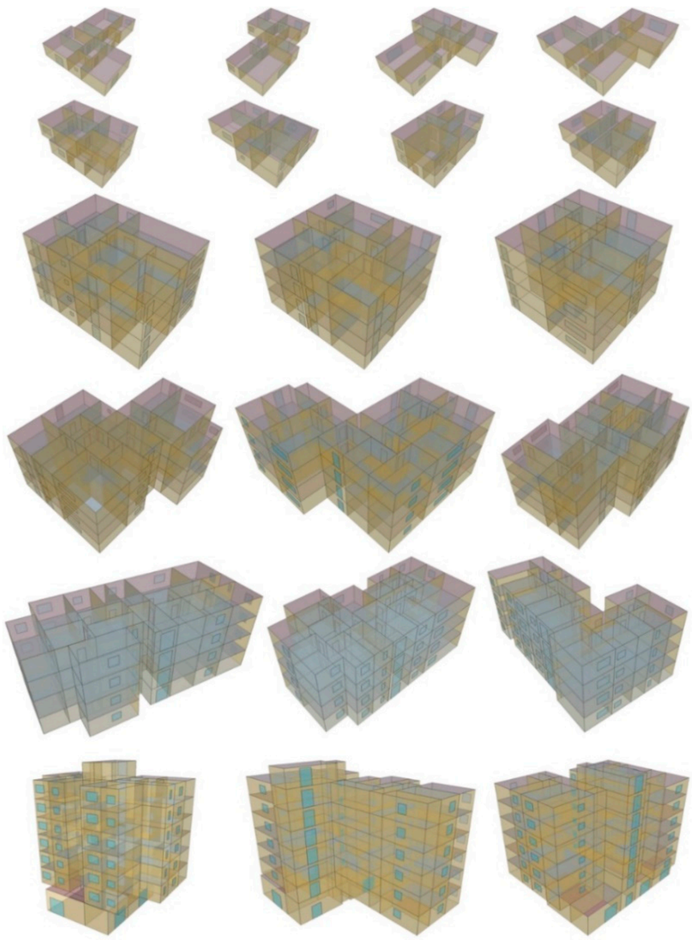

Figure 10. Examples of the generated buildings ranging from the single-storey family house to multi-storey mixed-use apartment buildings.

The simulation ran in a computer with an i7-8700 CPU, 32 GB of RAM. The PostgreSQL database was running locally on this computer. The *building_simulated* and *room_simulated* tables were populated with the transformed procedurally generated 3D models, which were referenced to the data from the

Slovenian building cadastre for the whole country (the data can be accessed from the link provided in the supplementary materials). We evaluated the performance of the simulation process and of selected SQL queries, aiming to check the data validity.

We selected the second approach for referencing the generated models to real cadastral data and thus get a degree of randomness in the simulated dataset. The transformation of the generated models was performed using FME Desktop software (the processing routine can be accessed from the link provided in the supplementary materials). The models with a higher number of storeys were more demanding in terms of processing time (a single-storey took 3 min, 2-storey 4 min, 4-storey 14 min, and 8-storey 37 min). The most demanding step in the transformation process is the creation of solid geometries. The referencing of the transformed models was performed in the PostgreSQL database using the SQL queries. The *building_simulated* table was created using a modified A3 SQL query (Appendix A.5—modifications of Appendix A.3 in bold text). The modification adds the classification of the buildings into four classes by the number of storeys. The SQL query A4 that selects data for *room_simulated* data was used without modifications. The SQL query execution times for creating *building_simulated* and *room_simulated* tables took 2 min 44 s and 12 min 35 s to process 512,191 (table size of 352 MB) and 10,985,775 (9274 MB) rows, respectively. After creating the tables, an index on the geometry column was created, and the VACUUM ANALYZE operation was performed to increase the performance of spatial queries.

With the data in the database, the performance of various processes and applications related to 3D cadastral data can be tested. We tested the performance of 3D queries that are designed to check the data for inconsistencies. For this, 3D functions from the PostGIS SFCGAL extension were used. SFCGAL is a C++ wrapper library that supports ISO 19107:2013, and OGC Simple Features Access 1.2 for 3D operations. The library is built around CGAL (Computational Geometry Algorithms Library), which provides algorithms for geometric computation [62].

The first SQL query checks for the intersection of 3D geometries in *building_simulated* table (Appendix A.6). The intersection of two building geometries represents an error, whether the geometries represent the physical or legal extent of the building. The placement of the models is performed using the centroids of real buildings. As the extents of real buildings and the procedurally generated models do not coincide, it is likely that some geometries intersect. The function that checks for the intersection is a Boolean-type function *ST_3DIntersects*. It has two arguments, representing two geometries that are checked for the intersection. A condition is added to exclude checking two identical geometries for the intersection (*a.id_building* != *b.id_building*). The function returns a TRUE value when parts of geometries are overlapping or if they touch each other. From the cadastral point of view, these two relationships are different, as touching of legal units is not forbidden, while overlapping is. There is no option to differentiate these two relationships without using additional 3D functions. The function uses the available spatial indexes to increase the performance. It took 2 min to find 128,812 intersections in the *building_simulated* table.

While the first query checked for the intersection of exterior geometries, the second one focused on identifying the room geometries that intersect each other (Appendix A.7). These intersections need to be checked separately for each building as the first query has checked intersections between exterior geometries of buildings. In our case, the room geometries are used to define the extents of the real property units (see Figure 4). Overlapping room geometries thus represent an error also in 3D cadastral context, as real property units are generally not allowed to spatially intersect each other. All the adjacent room geometries in the simulated dataset are in a touching relationship, which means that the *ST_3DIntersects* function identifies these as intersecting ones. As stated, there is no straightforward option to differentiate between touching and overlapping geometries when using PostGIS SFCGAL functions. Therefore, in the second query, the *ST_3DIntersection* function was used, which constructs 3D geometries that represent the intersections. If we calculate the volume of this intersection, it is possible to differentiate between touching and overlapping relationships. However, the *ST_3DIntersection* function is more demanding to execute than *ST_3DIntersects* as it returns the geometry of the intersection rather than the Boolean TRUE or FALSE. The query A7 selects the building identifier and identifiers of the pairs of rooms that overlap. The rooms are checked only against other rooms in the same building (*a.id_building* = *b.id_building*), excluding checking of the intersection of a room with itself (*a.id_room* != *b.id_room*). As the *ST_3DIntersection* function is computationally very demanding, only one building with four storeys was checked for overlap, which took 10 min to execute. The fact that the neighbouring room geometries are all in a touching relationship results in a large number of pairs of room geometries (389) to be checked with the *ST_3DIntersection* function.

The third error in the data that was checked was the intersection of room geometries with building exterior geometry. If the intersection is found, it means that the building exterior geometry does not enclose all room geometries. The room geometries can be checked for intersection with the corresponding building exterior geometry in the *building_simulated* table (Appendix A.8). The query was tested on the dataset for the whole country. The query execution time was 5 h and 18 min.

All 3D spatial queries except those containing the *ST_3DIntersection* function performed well with the complete dataset. This function validates both input geometries, which uses the majority of the processing time. However, if the input geometries are correct, this validation is not necessary. While the SFCGAL library allows disabling the validity check, the PostGIS SFCGAL implementation does not allow this.

To evaluate the performance of 3D visualisation, the simulated dataset is converted to a KML file for visualisation in Google Earth, and to 3D tiles for visualisation in Cesium. Both conversions were performed using FME Desktop software. As the KML file containing all 512,191 buildings from the *building_simulated* table failed to load in Google Earth (waiting time of 2 h), multiple KML files that varied in size to test the performance were created. The KML files were created with the feature count limit of 10,000, 5000 and 1000. The performance of KML file generation and loading time are roughly proportional to the feature count: 1000, 5000 and 10,000 took 7 s, 25 s, and 54 s, respectively, for file creation and 12 s, 70 s and 150 s, respectively, for loading into Google Earth. Once the files were loaded, the performance of the 3D visualisation (pan, zoom, rotate) was good in all cases (Figure 11).

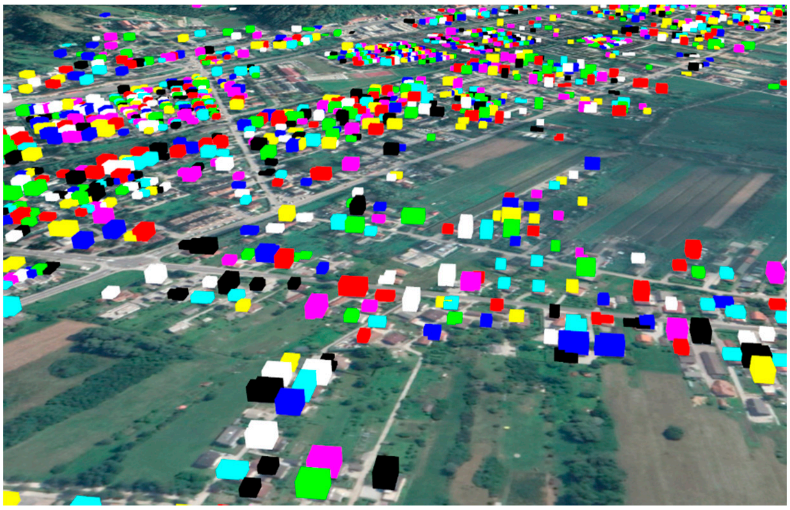

Figure 11. 3D visualisation of 3D visualisation of georeferenced simulated residential 3D building in Google Earth.

For the visualisation in Cesium, 3D tiles of buildings were prepared from the *building_simulated* table (512,191 records) and rooms in the *room_simulated* table (10,969,100 records). It took FME 6 min to create 3D tiles for buildings and 4 h 35 min for rooms. For testing purposes, Cesuim was run locally on an Apache Tomcat web server using the same PC that was used for other tests. A simple web application that visualises 3D tiles on the globe was used. Compared to the performance of 3D visualisation in Google Earth, Cesium effectively handled 3D visualisation of buildings and rooms for the whole country.

The proposed approach proved to be efficient for the simulation of large-scale 3D cadastral datasets for buildings referenced to some basic characteristics of the existing cadastral data, such as building location and number of storeys. The execution times of all steps needed to generate the simulated dataset are acceptable, given that we performed the simulation for the whole country, i.e., for the case of all 512,191 residential buildings in Slovenia.

4. Discussion

In this study, the location of the real buildings and the number of storeys are used to make the generated dataset more representative. Although the building generation algorithm allows us to specify other aspects of real buildings (area and dimension limits, height, etc.), the algorithm was left free to generate buildings from interior spatial requirements, such as to satisfy minimum room dimensions and minimum storey areas, in the proposed approach. This led to real buildings with a large footprint being assigned simulated buildings that were too small and vice versa. Consequently, the SQL query A6 identifies the intersections of the building geometries, that do not intersect in reality. Therefore, future developments will require the generated buildings to be produced within the statistical distribution of the real data. For a perfect match scenario, the simulated buildings would have to be generated exactly according to each real building in the country. In addition, there are computational and information limitations to overcome in the future. In the presented approach, the simulation is limited to residential buildings. When the building type information in the real cadastral dataset and higher computational capacity for generation of buildings are available, the approach may be improved to include also other types of buildings, such as schools, hospitals and offices.

Regarding the assignment of real property unit identifiers to rooms, various methods can be used. Using these identifiers, the 3D geometries of rooms can be aggregated to represent the extents of a real property unit. The identifier can be assigned using the storey and/or apartment number. Another option is to obtain the number of real property units from the existing cadastral data or real property registry. In this case, the assignment of identifiers to the simulated building is more challenging to simulate. One option is to assign the identifier to each room randomly. To obtain more representative real property units, the adjacency of rooms would have to be considered. This way, we would generate groups of adjacent rooms, which would get the same identifier assigned. Another option is to combine the apartment units to get the desired number of real property units.

Depending on the data model that we test, the 3D geometries of adjacent rooms that belong to the same real property unit can be joined into one 3D geometry of a real property unit. This removes the internal borders of rooms and preserves only the exterior boundaries of the group of adjacent rooms. This principle, using 2D geometries of the joined rooms representing a real property unit in one storey, is used for registration of buildings in Slovenia, where for new cadastral entries, 2D outlines of real property units are registered separately for each storey.

Besides the simulated buildings, the BIM datasets could also be integrated into the simulation process. In the studies that combine BIM and 3D cadastre, the *IfcSpace* entity is used for modelling 3D legal spaces [56,59]. The proposed method in this study uses FME Desktop software, which can be used to extract the *IfcSpace* entities and obtain the 3D building model. The structure of such a model is comparable to the simulated building model, but it is much closer to the real building. However, given the small amount of available BIM data that is available, the current potential of including BIM datasets is limited.

Compared to the approaches of Ledoux and Meijers [36] and Biljecki et al. [37], which also use existing data on buildings for 3D modelling, the proposed method is focused on generating 3D building models from its interior arrangements. Regarding external 3D geometry of buildings, our method underperforms due to external 3D geometry being a consequence of the interior arrangement. Thus, the other two methods are demonstrated to be more representative of reality in this aspect.

The executed queries demonstrate how the simulated 3D cadastral dataset can be used to define 3D cadastral data management strategies. Based on the executed queries, we can see that the queries containing the *ST_3DIntersection* function are too demanding to be used for regular checks of the whole cadastral database. Instead, these queries can be used to ensure the data validity at the moment of insertion or when some of the geometries are modified. In these cases, the new or modified geometry does not need to be checked against all geometries in the database, but only against a small subset.

5. Conclusions

In this study, a methodology to generate a not yet existing 3D cadastral dataset for buildings has been presented, thus answering the paradox of "how to get a complete dataset of something that is still in the design phase". The proposed method for simulating the 3D cadastral dataset was successfully applied for the case of Slovenia, thus proving that it can be efficiently applied to large areas. The evaluation of the database performance was illustrated with three spatial SQL queries, designed to check for the errors related to spatial relationships of 3D geometries. The adjacent geometries of the real property units in cadastre are generally in a touching relationship. The *ST_3DIntersection* function is needed to distinguish between the touching and overlapping relationship of two geometries, of which the first is allowed and the second represents an error. The tests showed poor performance of the queries that contain the *ST_3DIntersection* function. Therefore, based on the results of the performance tests of SQL queries, we can conclude that it is beneficial to have a representative dataset available in the design phase of 3D cadastral information systems. This allows us to identify problems and critical issues during the early stages of development and develop optimal DBMS storage and data management processes for cadastral data. The evaluation of 3D visualisation options shows that using 3D tiles and Cesium platform is a better option than using KML files and Google Earth, as 3D tiles are designed for visualisation of large 3D datasets. Cesium platform has therefore proved to be suitable for visualisation of large-scale 3D cadastral datasets.

Further enhancements of the presented method can be performed if additional parameters and attributes are provided for the buildings and parts of buildings, such as room types, their number, and area of each room per storey. The presented method needs further investigations to include also other aspects of real buildings into the building generation process, such as footprint area or outline, volume, and height. The developed method can also be used outside of 3D cadastral domain to develop spatial analytical tools for buildings in a 3D environment, which is also an open research area in the geospatial domain.

Supplementary Materials: The dataset of the 282 generated residential 3D buildings is available at the private link: https://doi.org/10.6084/m9.figshare.12283805. The dataset of building footprints from Slovenian building cadastre (Geodetska uprava Republike Slovenije, Grafični podatki katastra stavb, 11. 5. 2020) in shapefile format is available at: https://doi.org/10.6084/m9.figshare.12283760.v1. The projection is EPSG 3794. The processing routine for transforming each generated building (Section 2.2) is available at: https://doi.org/10.6084/m9.figshare.12288368.v1. The script can be run using FME desktop 2020 software.

Author Contributions: Conceptualization, Jernej Tekavec and Anka Lisec; Data curation, Jernej Tekavec and Eugénio Rodrigues; Formal analysis, Jernej Tekavec; Funding acquisition, Anka Lisec; Investigation, Jernej Tekavec, Anka Lisec and Eugénio Rodrigues; Methodology, Jernej Tekavec and Eugénio Rodrigues; Project administration, Anka Lisec; Resources, Jernej Tekavec, Anka Lisec and Eugénio Rodrigues; Software, Jernej Tekavec and Eugénio Rodrigues; Supervision, Anka Lisec; Validation, Jernej Tekavec and Eugénio Rodrigues; Visualization, Jernej Tekavec and Eugénio Rodrigues; Writing—original draft, Jernej Tekavec; Writing—review and editing, Jernej Tekavec, Anka Lisec and Eugénio Rodrigues. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0406 Earth observation and geoinformatics).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1. SQL Query to Select the Data for the Table Building_Simulated

```
SELECT id_building, id_bldg_gen, n_storeys,
ST_Translate(geom3d, ST_x(ST_GeometryN(geom_c,1)), ST_y(ST_GeometryN(geom_c,1)),h)
as geom3d
- translation of in the x ynd y direction using ST_Translate function
- from 0,0 to the x,y of the centroid of the real building
FROM cadastral_building
JOIN building ON building.n_storeys = cadastral_building.n_storeys
- To each building from existing cadastral data, join the simulated
- building with the appropriate number of storeys
```

Appendix A.2. SQL Query to Select the Data for the Table Room_Simulated

```
SELECT id_building, id_room_gen,
ST_Translate(room.geom3d, ST_x(ST_GeometryN(geom_c,1)), ST_y(ST_GeometryN(geom_c,1)),h)
as geom3d
- translation of in the x ynd y direction using ST_Translate function
- from 0,0 to the x,y of the centroid of the real building
FROM cadastral_building
JOIN building ON building.n_storeys = cadastral_building.n_storeys
JOIN room ON room.id_bldg_gen = building.id_bldg_gen
- To each building from existing cadastral data, join the simulated
- building with the appropriate number of storeys and then join all the
- rooms that to this building
```

Appendix A.3. Modified A1 SQL Query (Modifications in Bold Text) to Select the Data for the Table Building_Simulated

```
SELECT id_building, id_bldg_gen, n_storeys,
ST_Translate(geom3d, ST_x(ST_GeometryN(geom_c,1)), ST_y(ST_GeometryN(geom_c,1)),h)
as geom3d FROM (SELECT *, row_number() over(PARTITION BY id_building ORDER BY
random()) as rn
- More than one simulated buildings join to each real building. Randomly
- assign row number to those simulated buildings
FROM cadastral_building
JOIN building ON building.n_storeys = cadastral_building.n_storeys) a
WHERE a.rn = 1
- Take only the first of all the joined simulated buildings
```

Appendix A.4. Modified A2 SQL Query (Modifications in Bold Text) to Select the Data for the Table Room_Simulated

```
SELECT id_building, id_room_gen,
ST_Translate(room.geom3d, ST_x(ST_GeometryN(geom_c,1)), ST_y(ST_GeometryN(geom_c,1)),h)
as geom3d
FROM cadastral_building
JOIN building_simulated ON building_simulated.id_building = cadastral_building.id_building
- The simulated building is randomly selected.  Instead of joining the
```

```
- building table, we join building_simulated table
JOIN room ON room.id_bldg_gen = building_simulated.id_bldg_gen
- We can join the corresponding room geometries of the assigned
- simulated building
```

Appendix A.5. Modified A3 SQL Query (Modifications in Bold Text) to Select the Data for the Table Building_Simulated

```
SELECT id_building, id_bldg_gen, n_storeys, ST_Translate(geom3d,
ST_x(ST_GeometryN(geom_c,1)), ST_y(ST_GeometryN(geom_c,1)),h) as geom3d
FROM (SELECT *, row_number() over (PARTITION BY id_building ORDER BY random()) as rn
FROM cadastral_building JOIN building ON
CASE
WHEN cadastral_building.n_storeys >= 8
THEN building.n_storeys = 8
WHEN cadastral_building.n_storeys >= 3 AND
cadastral_building.n_storeys < 8
THEN building.n_storeys = 4
WHEN cadastral_building.n_storeys < 3
THEN building.n_storeys = cadastral_building.n_storeys
END) a WHERE a.rn = 1
- We limited the simulated buildings to 1, 2, 4 and 8 storeys. Real
- buildings have also other numbers of storeys.  The above addition
- assigns the appropriate simulated building to the real building.
- For example, real building with 5 storeys gets 4 storey simulated
- building assigned
```

Appendix A.6. SQL Query that Checks for the Intersection of 3D Geometries in Building_Simulated Table

```
SELECT a.id_building, b.id_building
FROM building_simulated a, building_simulated b
WHERE ST_3DIntersects(a.geom3d, b.geom3d)
- The contition - The output of the ST_3DIntersects function is boolean
AND a.id_building != b.id_building
- With this condition we exclude the checking of the geometry against
- itself
```

Appendix A.7. SQL Query that Checks for the Overlap of 3D Geometries in Room_Simulated Table

```
SELECT a.id_room, b.id_room, a.id_building FROM room_simulated a, room_simulated b
WHERE ST_3DIntersects(a.geom3d, b.geom3d)
AND ST_Volume(ST_MakeSolid(ST_3DIntersection(a.geom3d, b.geom3d))) != 0
- In addition to the ST_3DIntersects function, which is quick and removes
- all pairs that are not intersecting, we use ST_Intersection function
- and ST_Volume function to calculate the volume of the intersection. If
- the volume of the intersection is 0, then the geometries are in a
- touching relationship.
AND a.id_room != b.id_room
AND a.id_building = b.id_building
- In addition to excluding the checking of the geometry against
```

```
- itself, we use the condition to check only pairs of rooms in the
- same building
```

Appendix A.8. SQL Query that Checks for the Intersection of Room Geometries with Building Exterior Geometry

```
SELECT a.id_room, b.id_building FROM room_simulated a
JOIN building_simulated b ON a.id_building = b.id_building
WHERE ST_3DIntersects(a.geom3d, b.geom3d)
AND a.id_building = b.id_building
- This query has similar structure as A6.  Instead of checking the pairs
- of building geometries, this query checks for the intersection of
- building geometry with room geometries that belong to the building.
```

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Tekavec, J., Lisec, A. (2020b)

ISPRS International Journal of Geo-Information, 9(7), 417

DOI: 10.3390/ijgi9070417

Faktor vpliva za leto 2019: 2,239 (Q3)

International Journal of
Geo-Information

MDPI

Article

3D Geometry-Based Indoor Network Extraction for Navigation Applications Using SFCGAL

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Received: 29 May 2020; Accepted: 27 June 2020; Published: 29 June 2020

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Abstract: This study is focused on indoor navigation network extraction for navigation applications based on available 3D building data and using SFCGAL library, e.g. simple features computational geometry algorithms library. In this study, special attention is given to 3D cadastre and BIM (building information modelling) datasets, which have been used as data sources for 3D geometric indoor modelling. SFCGAL 3D functions are used for the extraction of an indoor network, which has been modelled in the form of indoor connectivity graphs based on 3D geometries of indoor features. The extraction is performed by the integration of extract transform load (ETL) software and the spatial database to support multiple data sources and provide access to SFCGAL functions. With this integrated approach, the current lack of straightforward software support for complex 3D spatial analyses is addressed. Based on the developed methodology, we perform and discuss the extraction of an indoor navigation network from 3D cadastral and BIM data. The efficiency and performance of the network analyses were evaluated using the processing and query execution times. The results show that the proposed methodology for geometry-based navigation network extraction of buildings is efficient and can be used with various types of 3D geometric indoor data.

Keywords: SFCGAL; DBMS; ETL; indoor navigation; topology; spatial query; 3D cadastre; BIM

1. Introduction

The 3D geospatial data domain with its derived 3D geospatial information and applications is experiencing rapid development in all its aspects, including 3D spatial data acquisition, spatial data modelling and processing, spatial analysis and visualization [1–4]. 3D geospatial data and 3D geoinformation applications have gained momentum in the past decade as a rapidly developing geospatial industry with new sensors and platforms, as well as the rapid progress of information and communication technology, opened up possibilities for acquiring, collecting, modelling and analysing big geospatial datasets. However, 3D spatial data management and analyses together with all aspects of indoor spatial data had been lagging behind until recently [5]. The spatial data queries and analyses for decision making and indoor applications require advanced data models with high-quality geometry and topology. While many publications deal with geometrical and topological approaches to 3D geospatial modelling [6–8], integrating and managing 3D geospatial data on both the geometrical and semantic levels remains a big challenge and is the focus of several research activities [9–11]. The importance of 3D spatial data integration and management lies in the fact that many spatial analyses that produce valuable information use data from various sources, which need to be harmonized and integrated. The current software support for 3D spatial data analysis is inadequate, as most algorithms support only 2D spatial data processing and analyses. The demand for and importance of indoor spatial information are rapidly growing, creating a need to integrate the data from different domains [2,12,13]. The extraction and modelling of data and information relevant for indoor navigation from various data sources has been intensively studied in recent years [14–18]. The main aim of this study is to develop a methodology to perform the extraction of an indoor navigation network based solely on 3D geometry using SFCGAL functions, and to discuss the issues and advantages in using this approach. The methodology is applied to two different indoor spatial data sources, i. e. 3D cadastre data and BIM data, which are well-known 3D geometric and attribute data sources for building interiors.

In the first part of the paper, the integration of spatial extract transform load (ETL) software [19] and the spatial database used to develop the methodology for geometry-based indoor navigation network extraction are presented. It is implemented using FME Desktop (FME) and PostgreSQL with PostGIS and SFCGAL [20] extensions. Assuming the ETL software supports the handling of 3D geometry, it can be effectively used for 3D geospatial data decomposition, integration, and data extraction, which is an important part of complex 3D spatial modelling and analyses. FME has strong support for 3D geospatial data manipulation and recently adopted standard data file formats such as CityGML [21], IndoorGML [22] and IFC (industry foundation classes) [23], together with other 3D data file formats (OBJ, COLLADA, STL, FBX, 3DS, and X3D). However, FME has some, though very limited, functionalities for processing 3D geometries. For this, the PostgreSQL database was selected as it provides access to SFCGAL 3D functions that enable processing of 3D geometries. The SFCGAL is a C++ wrapper library that supports ISO 19107:2013, and OGC (Open Geospatial Consortium) Simple Features Access 1.2 for 3D operations. The library is built around CGAL (Computational Geometry Algorithms Library), which provides algorithms for geometric computation. Besides the common spatial feature types, the PostGIS and SFCGAL enabled database supports storage of TINs (triangular irregular networks), polyhedral surfaces and solids, and offers functions to perform 3D spatial operations using the stored 3D geometries. As ETL software is designed to work with databases, it is common for ETL processes to include the databases. Our approach is different, as it uses the database for the access to 3D functions needed for extraction of an indoor navigation network based on 3D geometries.

The 3D cadastral case study aims to strengthen the idea of a multipurpose 3D cadastre. It builds on the 3D cadastral data model discussed in [24] with the difference that the solid geometries touch only at passages (e.g., doors). 3D geospatial data are to be used within a 3D cadastre to efficiently model the complex divisions of real property units in a 3D environment to which rights, restrictions and responsibilities are related [25]. Indoor navigation applications have generally been beyond the scope of traditional land administration, i.e., a cadastre. However, developments in 3D spatial data acquisition, management and visualization, especially in the last decade, have brought these two fields much closer [26]. Using cadastral data has some advantages over other data sources as the data is official, follows a predefined data model, and its quality is (or should be) controlled. The biggest current disadvantage is that the digital 3D cadastral systems are not yet introduced operationally at a larger scale.

The BIM data meeting IFC standards (ISO 16739-1:2018) represent a rich data source for many building-related applications, including indoor navigation. Diakité and Zlatanova [12] and Lin et al. [27] have already considered IFC data as a data source for indoor navigation applications. Xu et al. [28] and Lin et al. [17] propose reducing the problem to 2D space and rasterization of vector geometry. Xiong et al. [14] used voxelization to avoid complex vector processing tasks. A voxel model was also used by Staats et al. [29]. Teo and Cho [30] and Khan et al. [31] use semantic information (*IfcRelSpaceBoundary*) in IFC files for navigation network extraction. In contrast, our study is focused on the extraction of a navigation network based solely on the 3D geometry of *IfcSpace*, *IfcDoor* and *IfcStair* entities. Our approach is comparable to the approaches that propose the semantic-based extraction of a navigation network from an IFC file [30,31].

2. Methodology

The study focuses on the processing of 3D geometric data for extraction of an indoor navigation network. The 3D geometries that are used in this context are navigable 3D indoor spaces. To perform the 3D operations and to derive the navigation network from input data, we integrate the FME spatial ETL software and PostgreSQL database with PostGIS and SFCGAL extensions (Figure 1).

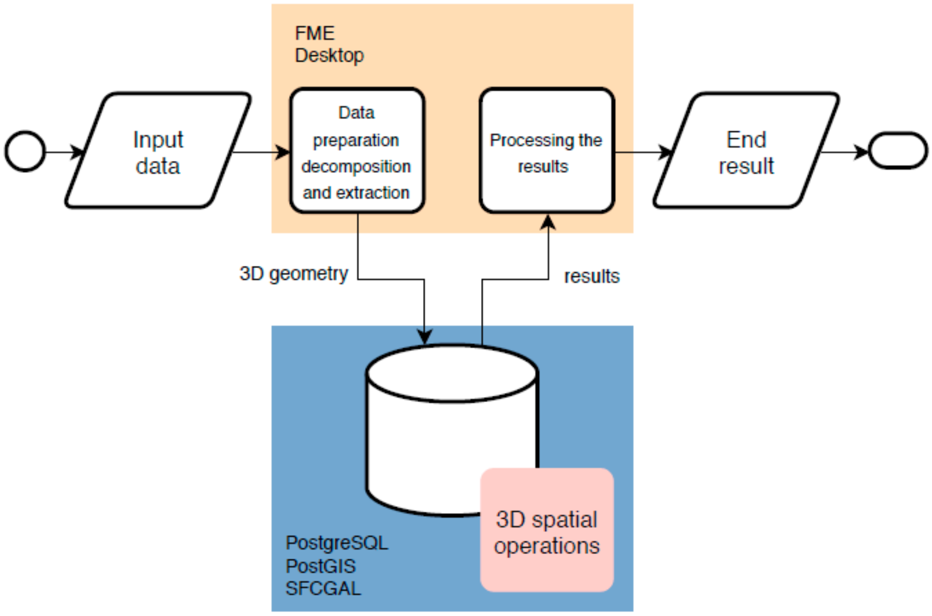

Figure 1. The concept of ETL-based data integration and 3D analytics.

Before the data is transferred into the database, it should be pre-processed. The aim is to extract 3D geometries and attributes from input data and transform them into a form that can be imported into the PostGIS database and analysed with SFCGAL functions. Firstly, all the relevant entities that represent 3D geometries of indoor features have to be extracted from input data. Some input datasets (for instance IFC files) have to be decomposed into separate entities first. The decomposition and extraction of relevant data can be performed during the import of the dataset into FME. After that, various attribute or geometry filters can also be applied to select the relevant data for 3D processing with SFCGAL functions. In this phase, depending on the data source, the geometries can be validated using FME tools and, to some degree, corrected for errors. The data storage usually terminates the ETL process. In this case, the data writing into the PostGIS database is performed during the process, allowing it to be continued after the data is loaded. The greatest attention in this phase should be given to the geometry, as only PostGIS-supported geometry types can be inserted into the database. In this paper, the focus is on 3D solid geometries that are bounded by polyhedral surfaces. The bounding surfaces of the geometries can be obtained in FME by deaggregation of input geometries. When the input geometries are deaggregated (split into parts), it is important to preserve their unique attributes. These attributes are used to group the surfaces that bound each solid geometry when creating solid geometries. Due to different tolerances and definitions of solid geometries in FME and PostGIS, some of the geometries can be reported as invalid in PostGIS. Figure 2 shows an example of a valid 3D solid in FME (no solid validation errors reported) (a) before and (b) after insertion into PostGIS database. In this case, the bounding surfaces in PostGIS are not the same as in FME. This happens with the surfaces that have internal holes. Such geometries are reported by PostGIS as invalid. PostGIS also reports the validity error, when the points of the same surface do not lie on the same plane. Such geometries do not allow the use of SFCGAL 3D functions in the PostGIS database. The generic solution for this issue is to perform the triangulation of all surfaces in FME before creating solid geometries. This additional step makes all bounding surfaces of solids triangles. With triangles, we avoid the validity issues as they do not have internal holes and also cannot have points not lying on the same plane.

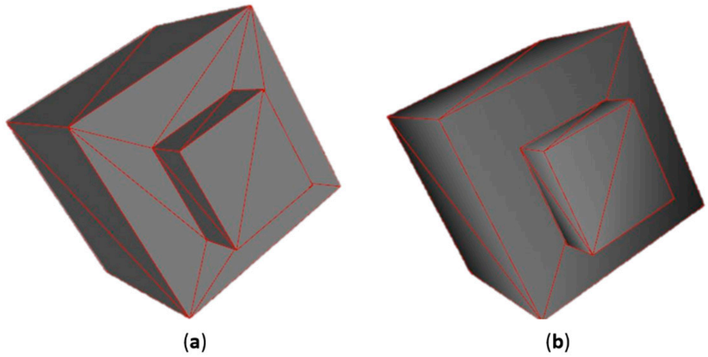

Figure 2. (**a**) Solid geometry in FME and (**b**) polyhedral surface inserted into PostGIS.

It should be noted that the triangulation changes the structure of the bounding surfaces, but this is not an issue for the presented application for geometry-based navigation network extraction. The geometries should be imported into the database together with identifiers to enable referencing the results of 3D operations in FME for later processing and writing of the results.

When the geometries (*geom*), identifiers (*sn*) and optional additional attributes are imported into the database (temporary table *spaces*), the SQL queries using SFCGAL 3D functions can be executed to derive the topological relationships of the inserted geometries. Generally, the navigable spaces that are in a touching relationship allow the transition from one to another. Some data models also allow the overlapping of navigable spaces that allow the transition. Here, we presume that the navigable spaces that are spatially disjoint do not allow the transition from one to another. Depending on the required complexity of the network, various methods can be used.

The first and most basic method uses the FME centroid placement tool and the SFCGAL *ST_3DIntersects* Boolean function to identify the pairs of geometries that intersect. The function returns TRUE for both overlapping and touching geometries. Using the query (Appendix A.1), we select two symmetrical pairs of identifiers (as *start* and *end*) per each connection of spaces that are found. If we want only one of the two pairs, the $a.sn! = b.sn$ condition should be changed to $a.sn > b.sn$. The query results in the identifiers of the connected spaces. Parallel to query execution in the database, the 3D solid geometries are transformed to graph nodes using the FME centroid placement tool. The algorithm has an option to force the placement of the centroid inside the polygon, thus solving the issue of the external centroid for complex polygons (concave and doughnut polygons). As only 2D polygons are supported, each 3D solid geometry is converted to a 2D polygon representing an outline of each solid in the horizontal plane. Each node is vertically placed in the middle between the vertical bounds of the corresponding solid. The final navigation network is realized by joining the nodes to the result of the SQL query and creating the lines between connected nodes. The first approach results in a basic navigation network, also known as node-relation structure (NRS) [32], with connections that do not represent the path between the nodes (Figure 3). Consequently, such a network can be used for basic navigation applications without an option for visualization of the path. Boguslawski et al. [33] and Liu and Zlatanova [34] use this type of network as the basis for derivation of more complex navigable networks.

The second method provides enrichment of the original NRS to node-relation structure and entrance (NRSE) [32]. To perform this using SFCGAL, the *ST_3DIntersection* function is introduced, which outputs the geometry of the intersection (Appendix A.2). Using the intersection geometries and FME centroid placing tool, the additional nodes, placed at space connections, can be derived and added to the navigation network (Figure 4).

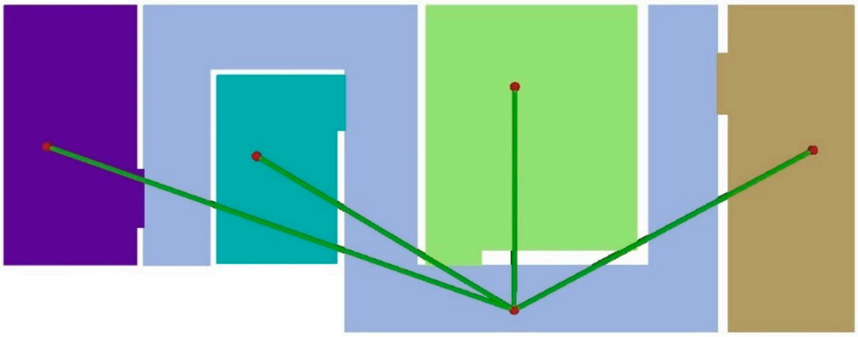

Figure 3. Basic indoor navigation network (NRS) with red nodes and green connections.

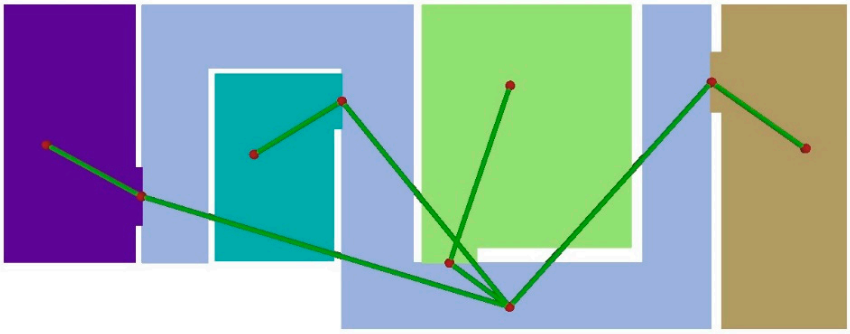

Figure 4. Node-relation structure and entrance (NRSE) navigation network with red nodes and green connections.

The method works for spaces that have only one connection to each connected space (Figure 4). Figure 5a shows an example of two spaces that are connected with multiple passages. Therefore, the method for NRSE derivation has to be modified to accommodate such cases. In these cases, the *ST_3DIntersection* function returns multiple intersection geometries as one feature. The FME deaggregator tool was used to split the spatially disjoint intersection geometries and thus place a node to each connection (Figure 5b).

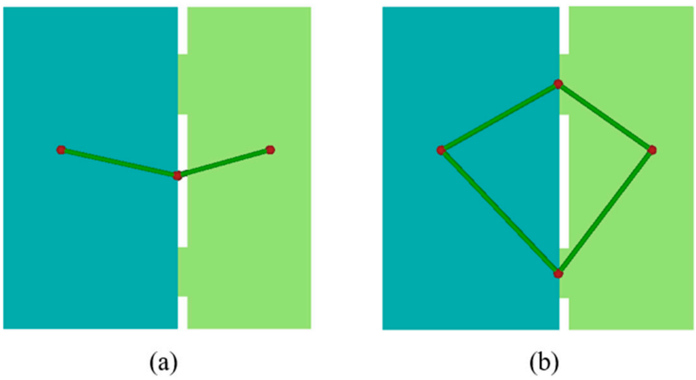

Figure 5. Basic NRSE derivation method (**a**) and the modified method for spaces with multiple connections (**b**).

As shown in Figures 3 and 4, the complexity of indoor spaces requires more advanced approaches that increase the number of nodes and optimize their placement. Many studies proposed various methods to derive the navigation network for optimal path planning. Most of them use methods that include medial axis transformation [30,32,35], structure segmentation using triangulated irregular networks (TINs) [18,33]. The SFCGAL function *ST_ApproximateMedialAxis* is used in the third proposed method that densifies the navigation network inside each space. As the function works only on 2D geometries, the solid geometries are transformed to their 2D outlines in FME and inserted into the PostGIS database (temporary table *spaces2d*) as polygons (*geom*) together with the identifiers of spaces (*sn*). There, the approximate medial axis is calculated for each polygon, obtaining the network edges (Appendix A.3). The *ST_Dump* function is used to derive the nodes of the calculated edges (Appendix A.4). At this stage, the calculated networks are not connected. The connection nodes of spaces are derived according to the second method and inserted into the PostGIS database (temporary table *connections*) with unique identifier (*id*) geometry (*geom*) and identifiers of both connected spaces (*start*, *end*). After joining the calculated edges (the result of the Appendix A.3 query) to the *connections* table, the nearest point on edge can be found using *ST_ClosestPoint* function that is included in standard PostGIS functions (Appendix A.5). This enables the connection of individual navigation networks into the final navigation network (Figure 6).

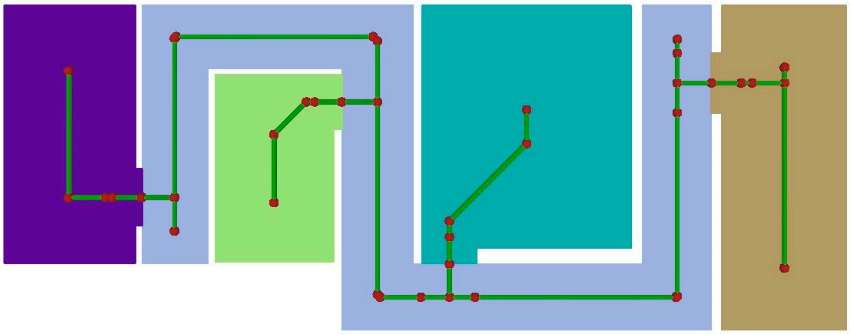

Figure 6. The result of the third proposed method.

3. Results

3.1. Navigation Network from 3D Cadastral Data

For the 3D cadastral case study, the input data is focused on buildings and can be characterized as a 3D version of traditional 2D floor plans used for condominium registration. The scope of the selected dataset used in the case study is limited to cadastral data, which is focused on the representation of the legal situation (e.g., real property units) using indoor spaces as a core spatial unit, defined by the physical structure of the building. Referencing the legal situation to the building's physical structure for condominium or strata title registration using 2D floor plans is known in many countries worldwide. The 3D indoor spaces, modelled with solid geometries, represent the core of the test data model that has also been discussed in [24]. As the focus of the case study was on testing the performance of the developed methods, four generic 3D cadastral datasets were used, consisting of one, three, six and nine storeys with the same horizontal layout and one vertical connection per floor (Figure 7). The test datasets were modelled using SketchUp 3D modelling software. The connections between indoor spaces (e.g., doors) are materialized by shared surfaces which enable extraction of the topology information using the SFCGAL 3D geometry functions. The real property units can be derived by aggregation of the corresponding spaces, i.e., spatial units. It is possible to apply the proposed methods to any other 3D cadastral dataset if the data format is supported by the FME and if it follows the same data modelling principle, having 3D geometries of indoor spaces in touching relationships. The approach for modelling such datasets from existing 2D documentation, which can be found in many countries worldwide, has been proposed in [24].

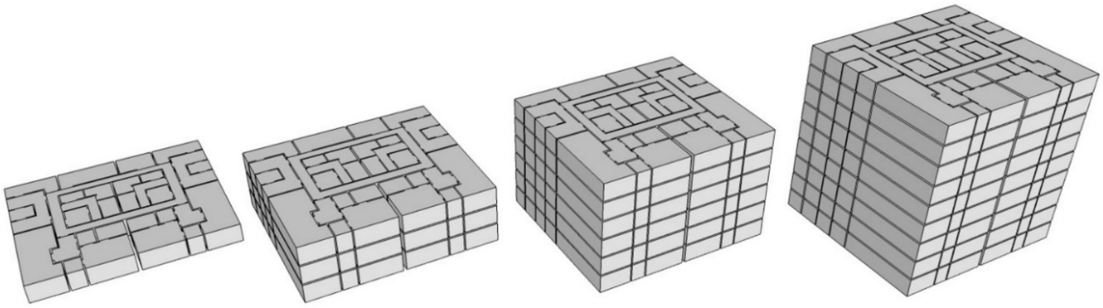

Figure 7. The 3D cadastral datasets.

All the test datasets were processed with all three presented methods in order to assess the performance of each method and the SQL queries included in each method. The processing times are used as results. While they enable relative comparisons, they depend heavily on the hardware that is used for processing. All the tests were performed on a PC equipped with i7-8565U CPU, 16 GB RAM and an SSD hard drive. Table 1 summarizes the processing results for the first and second method. Table 2 summarizes the results for the third method. For each method, a complete processing time is given, including all processes in FME and PostGIS. Additionally, the query execution times are given for each query that is included in the method. The processing times for Query Appendix A.2 in Table 2 are repeated from Table 1, as both the query and the data are identical for both methods Appendix A.

Table 1. Results of processing of the 3D cadastral datasets for the first and the second method.

Dataset	No. of Spaces	Method 1	Query Appendix A.1	Method 2	Query Appendix A.2
1 storey	31	29 s	0.08 s	1 min 10 s	42 s
3 storeys	93	59 s	1.4 s	3 min 8 s	2 min 25 s
6 storeys	186	1 min 46 s	7.1 s	6 min 39 s	4 min 28 s
9 storeys	279	2 min 58 s	16.2 s	10 min 16 s	6 min 30 s

Table 2. Results of processing of the 3D cadastral datasets for the third method.

Dataset	No. of Spaces	Method 3	Query Appendix A.2	Query Appendix A.3	Query Appendix A.4	Query Appendix A.5
1 storey	31	1 min 11 s	42 s	0.02 s	0.02 s	0.04 s
3 storeys	93	3 min 13 s	2 min 25 s	0.04 s	0.06 s	0.1 s
6 storeys	186	6 min 40 s	4 min 28 s	0.08 s	0.1 s	0.2 s
9 storeys	279	10 min 20 s	6 min 30 s	0.1 s	0.2 s	0.3 s

3.2. Navigation Network from IFC Data

The second case study is based on the example project IFC file from BIMcollab [36] for the office type building (Figure 8). Since many versions of IFC models exist, it should be emphasized that our method can be successfully applied only to the models that contain the *IfcSpace*, *IfcDoor* and *IfcStair* entities.

The input IFC file was imported and decomposed in FME, allowing the selection of individual IFC entities. First, we limited the selection of entities to *IfcSpace*, *IfcDoor*. We filtered the geometries by the type of geometry, where only solid geometries were passed through. Another filter passes only door solids with *Name* attribute value "Box" and space solids with *Name* attribute value "Body". For doors, the Box geometry representation was selected due to complex Body geometry representation. The geometries of doors and spaces were inserted into the PostGIS database (tables *spaces* and *doors*), where a query (Appendix A.6) was executed, selecting the doors and spaces that intersect in 3D space. This process is aligned with our first method (using only the *ST_3DIntersects* function), but gives results similar to the second method (NRSE), as doors are included as spaces. This approach can be used to extract a navigation network for one floor as it lacks vertical connections that are modelled with *IfcStair* entities. To add them, we select *IfcStair* solid geometries with *Name* attribute value "Box" and insert them into the database (table *stairs*). The union of three queries (Appendix A.7) selects pairs of intersecting doors and spaces, pairs of intersecting spaces and stairs, and pairs of intersecting stairs. Figure 9 shows the navigation network derived from the result of these queries. The result contains the connections between all features that are in an intersecting relationship. Some doors intersect with spaces that are on a different floor, resulting in non-existent vertical connections between spaces (blue lines in Figure 9). To avoid the extraction of these connections, the query Appendix A.7 was replaced with three separate queries (Appendix A.8) with one using the *ST_3Dintersection* function that outputs the geometry of the intersection. The non-existent connections were filtered in FME using the vertical extent of the intersection geometries.

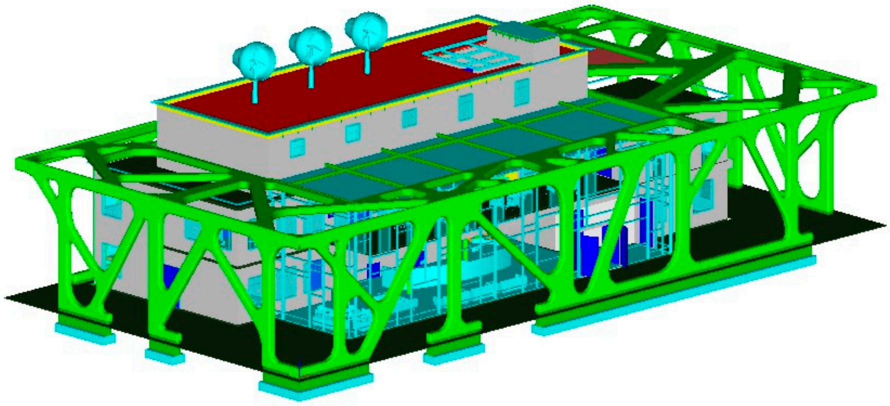

Figure 8. IFC test dataset [36] visualized using the FZK Viewer.

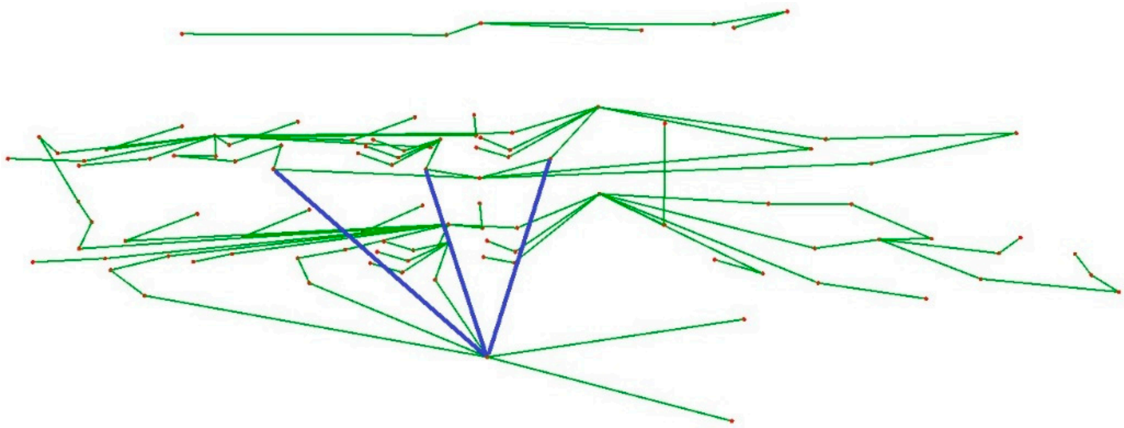

Figure 9. Navigation network derived from the IFC dataset using the first method.

Secondly, we applied the third proposed method that uses the SFCGAL function *ST_ApproximateMedialAxis* to densify the navigation network and make it suitable for path planning applications. Figure 10 shows the navigation network obtained by applying the third method.

Table 3 summarizes the results of processing the test IFC file that contains 51 *IfcSpace*, 58 *IfcDoor* and 3 *IfcStair* entities. The first method that generated the NRSE network structure was implemented using Appendices A.6–A.8 queries, while the third method was implemented using the Appendix A.8 queries, together with queries Appendices A.3–A.5 for calculating the approximate medial axes and finding the closest connection points on them.

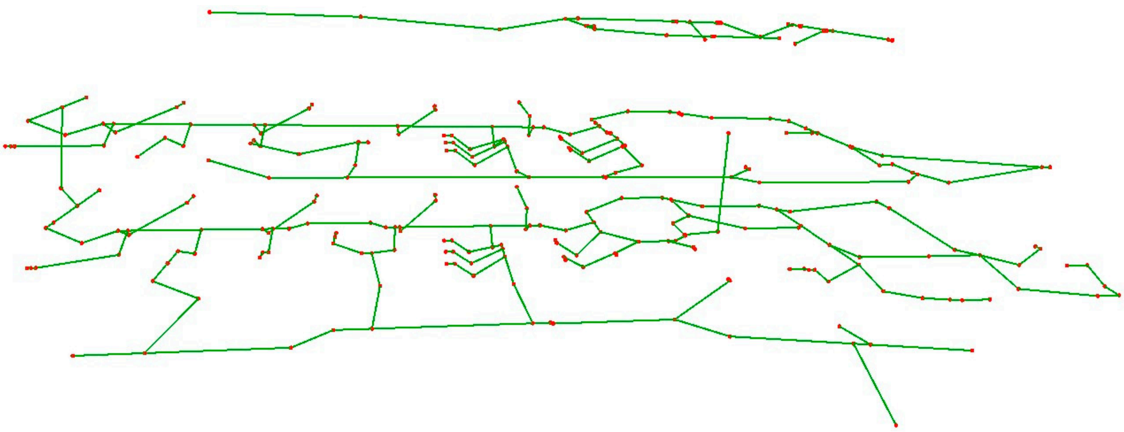

Figure 10. Navigation network derived from the IFC dataset by applying the third method.

Table 3. Results of processing of the 3D cadastral datasets for the third method.

Method	No. of Edges	Query	Query Time	Processing Time
Method 1	109	Appendix A.6	0.2 s	9.6 s
Method 1	113	Appendix A.7	0.2 s	10 s
Method 1	110	Appendix A.8	56.6 s	1 min 5 s
Method 3	157	Appendix A.8+ Appendix A.3 + Appendix A.4 + Appendix A.5	56.8 s	1 min 9 s

4. Discussion

The proposed methods for indoor navigation network extraction use advanced SFCGAL functions that process the geometries in 3D. This enables us to work fully automatically with 3D data, depending only on geometry. In 2D, a similar approach can be used, but it requires the building to be divided into floors to avoid vertical overlap of features, which cannot be properly handled by 2D algorithms. The division depends on semantic information in building models or must be done manually. There is also the problem of assembling all processed floors into one vertically connected model. However, in some parts of the process, we also have to use 2D geometries. The first case is the centroid placement, and the second is the calculation of the approximate medial axis. Both processes are used to calculate the placement of the navigation network nodes. Before the transformation of geometries to 2D, their vertical bounds are calculated to enable 3D placement of the calculated nodes. We avoid the external centroids in 2D with the option in FME that guarantees the point to be inside the 2D polygon. The nodes are placed in 3D using the middle value of the vertical bounds of space geometries. In some cases, where the geometries of the spaces are more complex, the nodes can be placed outside of the 3D geometry of the space (Figure 11).

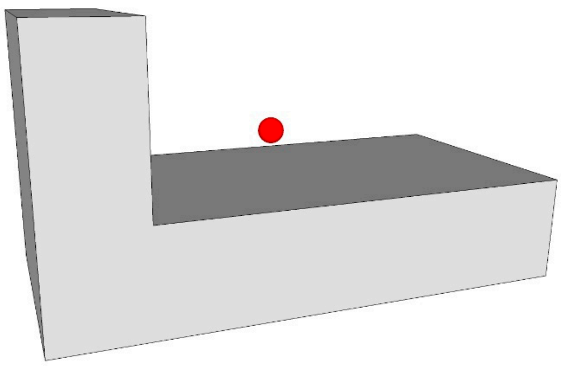

Figure 11. The node (red) placed out of the solid geometry due to variable ceiling height.

These errors can be found with additional processing in PostGIS. The nodes have to be inserted into PostGIS, where we can find the identifiers of solid geometries, which do not contain the corresponding node using the SQL query (Appendix A.9). The query uses the computationally demanding *ST_3DIntersection* function. The reason is that the *ST_3DIntersects* function does not work properly when comparing solid geometry and point geometry. Instead, the *ST_3DIntersection* function is used to check if the intersection geometry is empty, meaning the node is outside the corresponding solid geometry. Another option that avoids the presented errors is to create a vertical line for each node and intersect it with the space geometry (Figure 12) using an SQL query (Appendix A.10). The line is placed on the node location and has a larger vertical extent than the space geometry. The node that is inside the space geometry (red point) is between the calculated intersections (green points). Due to the usage of *ST_3DIntersection* function, both approaches significantly reduce the performance of the proposed methods, especially of the third method, where many network nodes are created for each space. Additional research is needed to improve the performance of the presented approaches for node placing inside 3D geometries.

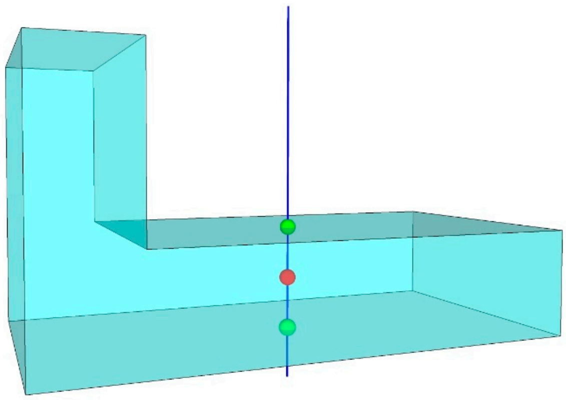

Figure 12. The line-space intersections (green) and the centroid (red).

The results of the first case study (Tables 1 and 2) show the best performance of the first method, which produces the most basic results. However, the results of the first method can be used as input for more advanced indoor navigation network extraction methods [33]. While the time share of SQL query Appendix A.1 execution time is low for the first method, the execution time of the SQL query Appendix A.2 represents the majority of the processing time of methods 2 and 3. This is caused by the SFCGAL *ST_3DIntersection* function being computationally much more demanding than the SFCGAL *ST_3DIntersects* function. The FME processing time remains roughly the same for all methods and increases linearly with the increase in the number of processed spaces. The difference in processing time for methods 2 and 3 is minimal as the query Appendix A.2 is the same for both methods. Additional queries in method 3 that calculate the approximate medial axes and their connections are basically non-significant in terms of execution time as they are all executed in less than 0.6 s for all cases. The 3D cadastral data model that is used in this case study has an additional advantage when it is processed using 3D functions. The intersection geometry calculated in methods 2 and 3 using *ST_3DIntersection* function is a surface. The SFCGAL function *ST_3DArea* can be used to calculate the area of an intersection to check if the passage is navigable for a particular locomotion type.

The results of the second case study (Table 3) prove that the proposed methods can be efficiently applied to IFC data if it contains the required entities (*IfcSpace*, *IfcDoor* and *IfcStair*). Since the IFC data model is standardized, any other IFC dataset that contains these entities can be processed the same way as the test dataset. Method 2 was not used in this case study as it aims to extract nodes at the connections of spaces (where they touch) and the *IfcSpace* geometries do not touch each other. In combination with *IfcDoor* geometries, method 1 produces similar results as method 2 in the first case study. The query A8 reduces the errors in the navigation network, but it requires the use of the *ST_3DIntersection* function, which significantly reduces the query performance.

In the cadastral data model, the stair spaces were modelled the same way as other spaces, which is not the case for the IFC data model. If the stairs are located inside the building, our approach successfully derived the vertical connections. Some *IfcStair* entities in the test dataset have no geometric contact with other *IfcStair* entities or any of the *IfcDoor* and *IfcSpace* entities, which caused some vertical connections to be left out. This can be seen in the upper part of Figures 9 and 10, where a part of the navigation network is not connected to the rest of the network. This represents a disadvantage of the geometry-based methods, as there is no option to extract the connection if the geometries of the features are spatially disjoint. In these cases, the methods that are based on semantic information have the advantage. We compared our approach to the semantic-based approaches [30,31], which use the *IfcRelSpaceBoundary* entities to extract the navigation network from IFC dataset. The comparison can be done only for the IFC models, that also contain the *IfcRelSpaceBoundary* entity. We joined the *RelatingSpace* attribute from the *IfcRelSpaceBoundary* entity to *IfcDoor*, thus getting information about *IfcDoor* and *IfcSpace* relations that were used to derive the navigation network. The process was very fast, as the connections were found based on the attributes. However, we found that the *IfcRelSpaceBoundary* entities contain errors, which caused some wrong connections between spaces and doors, shown in Figure 13. It should be noted that the files available in 2020 were altered and corrected for these errors.

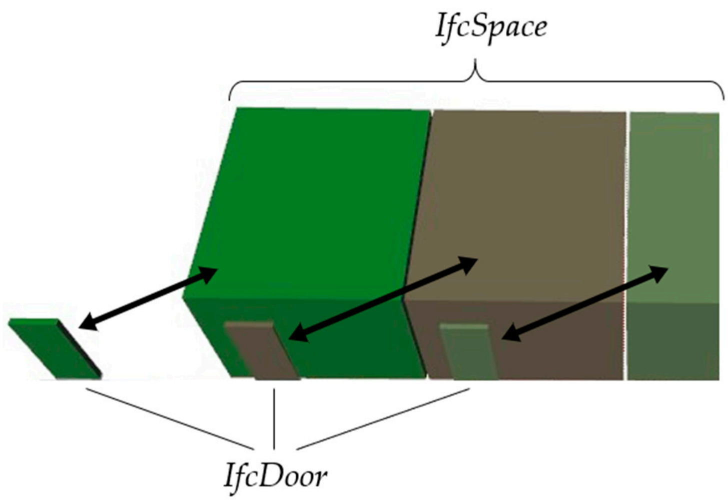

Figure 13. Errors in *IfcSpace* and *IfcDoor* (having equal colour) relations retrieved from the *IfcRelSpaceBoundary* entity.

The results of the case studies show that the quality of the extracted navigation network depends on several factors. The first is the data model of the input data, which determines how the input data is structured and modelled. Consequentially, it determines how well the input data supports the geometry-based navigation network extraction. In the case studies, the 3D cadastral dataset causes no issues with the extraction of navigation network for stairs, while for the IFC dataset, some vertical connections cannot be extracted based on SFCGAL geometry functions. As the paper is focused on the usage of SFCGAL functions, the quality of the extracted navigation network with the proposed methods is limited by the limited capabilities of those functions. For the third method, we use the *ST_ApproximateMedialAxis* function for the extraction of the navigation network inside each room. For larger spaces, it produces the network that is less appropriate for indoor path planning. More advanced solutions exist, which, on the other hand, rely on having the room connectivity available [33]. The options to integrate these solutions with the proposed methods need to be explored in the future to automatically obtain more advanced navigation networks, suitable for indoor path planning. Among the most important factors that affect the quality of the results are the errors in the input data. We demonstrated how the errors in the *IfcRelSpaceBoundary* entity affect the semantic-based navigation network extraction. The presented geometry-based approach is sensitive to geometry errors.

In the 3D cadastral data model, the connected indoor spaces should be in a touching relationship. In the process of 3D modelling or processing the input data, gaps between spaces may occur. These gaps cause the methods to fail in the extraction of connections. The possible solution for small gaps is rounding the coordinates, but it can make the gap even larger in some cases (for instance, 0.149 is rounded to 0.1, and 0.151 is rounded to 0.2). The solution would be to have a flexible tolerance setting for geometry processing, but this is not available for the SFCGAL functions. IFC entities can have multiple geometry representations. Due to the complexity of "Body" representation, less complex "Box" geometry representation is used in our case study for *IfcDoor* and *IfcStair* entities. Using these less complex geometries can cause some non-existent connections to be identified by our proposed methods. As stated before, the proposed methods can be applied to any IFC file that contains *IfcSpace*, *IfcDoor* and *IfcStair* entities, but one has to be aware of the presented limitations that can affect the quality of the extracted navigation network. Future research is needed to investigate the complementary use of the proposed geometry-based methods together with semantic-based approaches that are not affected by the invalid and too complex geometries.

5. Conclusions

The presented methodology for geometry-based indoor navigation network extraction is developed using SFCGAL functions that support 3D geometries. This allows the original 3D geometries of building models to be used in a process without dividing the building models into separate floors. The developed methodology enables the full automation of the process from input data import to the final result in the form of a navigation network. Three methods are developed to demonstrate the possibilities of using SFCGAL functions for geometry-based navigation network extraction. The methods differ in the complexity of the output navigation network. To achieve the flexibility in terms of input data and to provide access to SFCGAL functions, the FME spatial ETL software, supporting a wide range of data formats, was integrated with the PostGIS database, providing access to SFCGAL functions. Future research can investigate the possibilities to use alternative software to implement the proposed methods. A wide range of supported formats and flexibility of the FME software allows the proposed methods to be applied on various datasets that provide 3D indoor information besides the case study data (for instance CityGML LOD 4 models or DWG files), which also needs to be investigated in the future. The pre-processing of geometries is crucial for efficient implementation of the proposed methods. The deaggregation of various input geometry types and surface triangulation in FME proved to be an efficient approach for obtaining valid solid geometries in PostGIS that can be analysed using SFCGAL functions. SQL queries were used to process 3D geometries and extract connectivity information. Besides the navigation network extraction, this integration can be used to perform various 3D analyses of spatial data.

The case studies show that the proposed methods are efficient enough to enable processing of larger datasets. The case study with a 3D cadastral dataset aims to emphasize the multipurpose role of a 3D cadastral system and data in the future. While 3D geometries of indoor spaces significantly help with clarifying the legal situation in the building, they can, if properly structured, also support many new applications, including indoor navigation. The second case study showed some deficiencies of the presented methodology when applied to IFC data. Although most of the connections were identified and properly modelled in 3D, some connections were not found due to the methodology being purely geometry-based and fully automated. Additionally, the proposed methodology can be used to validate the *IfcRelSpaceBoundary* entities. In the test dataset, they provided some physically impossible connections that were discovered using the proposed methodology.

Author Contributions: Conceptualization, investigation, writing—review and editing, Jernej Tekavec and Anka Lisec; methodology, formal analysis, software, validation, visualization, writing—original draft preparation, Jernej Tekavec; supervision, Anka Lisec. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. P2-0406 Earth observation and geoinformatics).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Appendix A.1. SQL Query for Selection of Identifiers of Geometries that Intersect in 3D Space—Method 1

```
SELECT a.sn as start, b.sn as end FROM spaces a, spaces b
WHERE ST_3DIntersects(a.geom, b.geom) AND a.sn! = b.sn
```

Appendix A.2. SQL Query for Selection of Identifiers and Intersection Geometry of Geometries that Intersect in 3D Space—Method 2

```
SELECT a.sn as start, b.sn as end, ST_3DIntersection(a.geom, b.geom) FROM spaces a, spaces b
WHERE ST_3DIntersects(a.geom, b.geom) AND a.sn! = b.sn
```

Appendix A.3. SQL Query that Generates an Approximate Medial Axis for Each Space

```
SELECT sn, ST_ApproximateMedialAxis(geom) as geom FROM spaces2d
```

Appendix A.4. SQL Query that Generates Points from the Approximate Medial Axis for Each Space

```
SELECT sn, (ST_DumpPoints (ST_ApproximateMedialAxis(geom)).geom as geom FROM spaces2d
```

Appendix A.5. SQL Query that Finds Closest Points on Edges of the Connected Networks

```
SELECT a.id, b.sn, ST_ClosestPoint (b.geom, a.geom)
FROM connections a
INNER JOIN
(SELECT pn, ST_ApproximateMedialAxis (geom) as geom FROM spaces2d) b
ON a.start = b.sn OR a.end = b.sn
```

Appendix A.6. SQL Query for Selection of Intersecting Doors and Spaces

```
SELECT a.id as start, b.id as end FROM doors a
JOIN spaces b ON ST_3Dintersects (a.geom, b.geom)
```

Appendix A.7. SQL Query for Selection of Intersecting Doors, Spaces and Stairs

```
SELECT a.id as start, b.id as end FROM doors a
JOIN spaces b ON ST_3Dintersects (a.geom, b.geom)
UNION ALL
SELECT a.id as start, b.id as end FROM stairs a
JOIN spaces b ON ST_3Dintersects (a.geom, b.geom)
UNION ALL
SELECT a.id as start, b.id as end FROM stairs a
JOIN stairs b ON ST_3Dintersects (a.geom, b.geom)
AND a.id < b.id
```

Appendix A.8. SQL Queries for Selection of Intersecting Doors, Spaces and Stairs with Added Intersection Geometry for the Door–Space Intersections

```
SELECT a.id as start, b.id as end, ST_3DIntersection(a.geom, b.geom) FROM doors a
JOIN spaces b ON ST_3Dintersects (a.geom, b.geom)
SELECT a.id as start, b.id as end FROM stairs a
JOIN spaces b ON ST_3Dintersects (a.geom, b.geom)
SELECT a.id as start, b.id as end FROM stairs a
JOIN stairs b ON ST_3Dintersects (a.geom, b.geom)
```

```
AND a.gid < b.gid
```

Appendix A.9. SQL Query for Selection of Spaces which do not Contain the Corresponding Centroid

```
SELECT a.sn FROM spaces a, centroids b
WHERE a.sn = b.sn AND ST_IsEmpty (ST_3DIntersection(ST_MakeSolid (a.geom), b.geom))
```

Appendix A.10. SQL Query that Selects the Intersecting Points of Lines and Spaces for Centroid Placement in 3D

```
SELECT a.sn, ST_3DIntersection (a.geom, b.geom) FROM spaces a, lines b
WHERE a.sn = b.sn
```

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