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ORIGINAL ARTICLE

Crowdsourced 3D cadastral surveys: looking towards the next 10 years

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Abstract

Rapidly growing cities, multiple uses of urban space and the complexity of overlapping property rights require various types of rights to be registered and handled in a uniform and reliable way, considering the third dimension. The adoption of automated and low-cost but reliable procedures for cadastral surveys and for the capture and processing of cadastral data, as well as the use of modern Information Technology (IT) tools and m-services, is the beginning of a new cadastral evolution. 3D-crowdsourced cadastral data capture has huge potential and may soon facilitate the work of National Mapping Agencies (NMAs). In this paper, an innovative fit-for-purpose procedure is designed and initially tested that aims to save time and costs and to provide a modern technical solution for the initial collection, registration and visualization of 3D cadastral data. An open-source, mobile application for the acquisition of 3D crowdsourced cadastral data and 3D modelling and visualization of property units is developed, tested and presented. The proposed technical procedure is adjustable and may be used in both the developed and the developing world. The geometric accuracy of the final product depends on the geometric accuracy of the basemaps used. The developed application is tested on a multi-story building in an urban area of Larisa, in Greece. An initial evaluation of the procedure and the final product, in terms of its usability, affordability, reliability and implementation duration, is conducted. The first results are satisfactory and may lead to a fit-for-purpose procedure for a 3D cadastre for all in the future.

Keywords 3D cadastre · Crowdsourcing · 3D modelling · Land administration

JEL classification O43 · O47 · O17 · P14 · P25 · P26 · P48 · Q15 · R31 · R38 · R52 · F3

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1 Introduction

The World Health Organization (WHO) reported that in 2014, 54% of the world's people lived in urban areas, up from 34% in 1960. The tipping point, according to most authorities, occurred in 2007, when there were more urban dwellers than rural residents in the world: the so-called "urban millennium". The United Nations predict that by 2050, 66% of the world's population will live in urban areas. Much is being written about the growth of urban populations and the concurrent growth of urban geospatial infrastructures and institutions to support this huge growth of two-thirds of the world's population. Experts all over the world are working towards the same goal: trying to increase the "value" of geospatial data and urban geospatial infrastructures for society in order to achieve more benefit, more transparency, more safety, more environmental quality, more growth, more fairness, more efficiency in governance of urban areas and more smart cities. Of all the institutions that must be developed to anticipate, keep abreast of and support this growth, the cadastre stands foremost in the interest of commerce, real estate investment, municipal revenue and personal property security, not to mention urban planning and management. Geo-information professionals and cadastral experts all around the world are working together to develop services to deliver administrative, economic and social benefits, as well as fit-for-purpose land administration solutions and land policies for sustainable urban management. This paper presents the current results of an on-going research project that is aligned with this global effort, which aims to develop a practical technical tool for the future management of 3D property rights in urban areas.

Today, private property rights are recognized as a fundamental element of modern market economies. The recognition of the importance of private property rights has led in turn to the need for their registration in order to provide secure ownership of land and to support the operations of the property market and global economic development. As less than 30% of land has been registered in cadastral systems, land surveyors today focus their services on the purpose of a global registration of property rights and aim to provide a functional solution, reliably and affordably, for a complex and rapidly changing world that has adopted the 2030 UN Global Sustainable Development Agenda to address global challenges, among them, to eliminate poverty by 2030, so that no one will be left behind. The Sustainable Development Agenda 2030 target 1.4. recognizes that "by 2030, countries should ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance." (General Assembly Resolution 70/1 2015). In this effort, it has been recognized that traditional 2D cadastral surveys (of land parcels, property rights and responsibilities) are expensive and time-consuming. Therefore, research has been directed towards introducing modern, low-cost geospatial and cadastral data capturing methods, if possible using crowdsourcing methodology and mobile services, which will enable greater citizen participation in order to speed up the compilation of the cadastral surveying of the world's remaining unregistered 70% of land and reduce costs (Keenja et al. 2012; Basiouka and Potsiou 2012a, b, 2013; Basiouka et al. 2015; Enemark et al. 2014, 2015; Mourafetis et al. 2015; Apostolopoulos et al. 2016; Gkeli et al. 2016).

However, cities grow vertically as well as horizontally, thereby introducing the element of the third dimension. No reality has a more direct bearing on the subject of three-dimensional geoinformation and 3D cadastre than the growth of large cities, especially in the developing countries of the world, and in the phenomenon of mega cities. It is recognized that the current cadastral systems, based on two-dimensional cadastral maps, may not be efficient enough to visualize the exact boundaries of the 3D property units to which property rights may refer in complex urban areas in the near future, and therefore may not be reliable for supporting urban activities (Rautenbach et al. 2015a, 2016). The sustainable management of large and mega cities requires transparency and credibility in the determination of property rights at every level, bringing the 3D cadastre into the spotlight. 3D cadastre has been attracting researchers throughout the world for nearly a decade, bringing in line very interesting approaches describing how 2D cadastral systems should best be transformed into 3D cadastres. Some investigations have proposed the use of existing 3D data, collected in other areas, such as Building Information Models (BIM), Industry Foundation Class (IFC) CityGML files, IndoorGML, InfraGML and LandXML (Dimopoulou et al. 2016; Oldfield et al. 2016). Other researchers have investigated the use of procedural modelling for the generation of a 3D model (Gkeli et al. 2017a, b, c; Rautenbach et al. 2015b).

The utilization of already existing 3D data sources may facilitate the 3D building modelling procedure. The only disadvantage is their limited availability, failing to cover all possible implementations. Nevertheless, in the recent literature, numerous sources for 3D data acquisition have appeared, including Lidar data, aerial, terrestrial or spaceborne optical data, topographical data, terrestrial laser surveys, and data derived from crowdsourcing or volunteered geographic information (VGI) (Goodchild 2007a, b). In recent years, VGI and crowdsourcing methods have become more and more popular, while they constitute cost-effective, efficient and time-effective methods for 2D and 3D data acquisition. Therefore, the utilization of such data through model-driven methods tends to be the best option for a cost-effective and rapid implementation of 3D cadastral mapping, as it is considered to be simpler than time-consuming and protracted modelling processes. Over the years, many photogrammetric and digital image processing approaches have been developed and used in 3D modelling (Gkeli et al. 2017a, b, c). The development of an innovative parametric modelling algorithm appropriate for cadastral mapping purposes and the utilization of modern IT tools and data collection methods, such as crowdsourcing, may lead to a fast and cost-effective solution for the initial registration, building reconstruction and property unit visualization for a functional EU-desired 3D cadastral map (Gkeli et al. 2017a, b, c). Yet, most of the existing approaches are costly and time-consuming and not yet appropriate for serving the needs of countries with limited budgets, and are certainly not appropriate to serve the rapidly growing cities of the developing world that lack basic geospatial infrastructures. In addition, the rapid urban growth in the developing world is happening to a great extent informally, meaning among several other issues, that most of urban growth is happening on unregistered lands with limited or no documentation.

Keeping in mind that the need for a fit-for-purpose technical procedure for establishing a 2D cadastral system is urgent in the developing countries of the world today, there is a similar need for a fit-for-purpose procedure for a 3D cadastral system in the mega cities of the developing world as well. Thus, the current research in this field may also be directed towards developing inclusive solutions for the compilation of fit-for-purpose 3D cadastres reliably, affordably and in a timely manner to satisfy future urban needs and to support the Sustainable Developments Goals for 2030, in both developed and less developed areas. This paper aims to contribute towards developing an adjustable procedure that may work both for the developed and for the developing world, adaptable to all countries, wherever there may be the necessary political will to recognize, legally empower and register private property rights.

The main objective of this paper is to develop a procedure and to propose a more generalized technical framework for the initial registration of 3D crowdsourced cadastral data anywhere, exploiting the available cartographic infrastructure of each country and including regions that still lack registration of 2D cadastral data. The proposed framework aims at 3D crowdsourced cadastral data acquisition and 3D modelling and visualization of property units in a fast, reliable and affordable manner.

Section 2 presents several international approaches concerning actual or experimental implementation of a 3D cadastral system. Section 3 presents some international research initiatives related to 3D modelling utilizing 3D data collected mainly through VGI and crowdsourcing techniques. Section 4 combines experience and presents a framework describing an innovative cadastral procedure, while an open-source, mobile application for 3D cadastral data acquisition, 3D modelling and visualization of real properties is developed by the authors and presented in Sect. 4.1. Section 4.2 presents an implementation of the developed application in a multi-story building in the urban area of Larisa, in Greece, as well as the results of the overall procedure. Finally, Sect. 5 presents an assessment of the proposed procedure and of the achieved results in terms of usability, reliability, affordability and time–cost, as well as the main conclusions referring to the proposed framework for the initial implementation of a well-functioning fit-for-purpose 3D Cadastre.

2 3D cadastre in an international context

The third dimension in cadastre mainly facilitates subdivision of buildings into strata, creating separate property units above or below the original ground surface. The typical types of such property units are apartments or buildings registered as private properties, either separately from the land parcel they are built on, or related to the land parcel since the rights holders of those units may also be rights holders of shared ownership rights on the parcel as well as on the common areas of the building. Other facilities such as tunnels and underground construction such as transportation or utility networks, and privately owned underground commercial or public spaces, may also be registered in a 3D cadastre, or in a different register as separate property units. This paper focuses on developing a fit-for-purpose procedure and an inclusive, affordable, fast and reliable technical methodology for the registration process of 3D property units. Included are the rights and responsibilities attached to those units, as in multi-story, multi-unit buildings (whether or not held apart from the land parcel) and the individual parts/subdivisions of those buildings such as condominiums (however, dimensionally arranged). Such buildings usually have two components: the privately owned units and the jointly owned sections of the buildings. Many countries have developed clear legal procedures for the establishment and registration of rights of 3D property units in their cadastres. Moreover, during the last decade, many are considering interesting approaches to visualization of such data, and how their 2D cadastral systems may best be transformed into 3D cadastres that will include a 3D graphical representation of the property units and the rights associated with them. However, the most difficult phase in terms of costs and time demand is still the initial 3D cadastral data capture. Some examples of the progress achieved in this effort are given below.

One of the first countries to envision a 3D cadastre was Australia. Since the 1960s, freehold titles for 3D cadastral objects have been guided by the Land Title Act 1994. In 1997, 3D geometry could be represented as volumetric parcels in the cadastral system of Queensland (Stoter and van Oosterom 2005). 3D parcels have been accommodated in the Queensland cadastre via building parcels, restricted parcels, volumetric parcels and remainder parcels (Karki 2013). Despite developments legally, three-dimensional property information is included in the descriptive database without being accompanied by a three-dimensional representation. 3D properties appear as 2D on the cadastral map, accompanied by their titles and the three-dimensional information defined according to the regulations (strata titles). In Queensland, plans with 3D objects are *volumetric* plans, whereas in other states they are called *stratum* plans. All possible rights, restrictions and responsibilities that can be registered in 2D can also be registered as 3D parcels. Currently, Queensland is investing in the development of the 3D QLD initiative, aiming to provide 3D indoor navigation and 3D augmented reality through the cadastral database (http://3dqld.org/).

Another interesting example is the 3D Cadastre approach of Shenzhen, in China. Rapid urbanization has led to the development of mega cities in China with especially complex urban infrastructures. The traditional 2D cadastre could not manage the ever-expanding 3D urban planning and land-use processes. The Property Law of 2007 opened the way for the development of a 3D cadastre and registration system, and in 2012, a 3D cadastral management prototype was created in Shenzhen (Guo et al. 2014). This prototype includes the geometry of 3D property objects and compatible 3D data models, and generates 3D model data and 3D topologies. Although there is significant progress, the amendment of the relevant laws and regulations is essential in order to support the complete 3D data organization.

In 1999 and 2000, the Israeli government decided to improve land-use management in the country, including underground spaces and infrastructures, and recognized the necessity of a practical solution for the registration of rights in three dimensions (Benhamu 2006; Benhamu and Doytsher 2001, 2003). To promote the multi-layer use of land and its registration in strata, the Survey of Israel initiated a Research and Development project to find geodetic, cadastral, planning, engineering and legal solutions for a multi-layer 3D cadastre that will complement the existing 2D cadastre. The project was successfully completed during August 2004, and the first step towards a 3D cadastre was completed (Benhamu 2006).

Since 1990 in Taiwan, a digital method has been used for the resurvey of land following the land restitution of 1946. The original cadastral maps were digitized and completed in 2007. The cadastral maps are saved as tables of land parcels, boundaries and coordinates of the corners of properties in the database. A 3D cadastral system has been initiated in Taiwan since 2007 (Chiang 2012). The 2D raster floor plans must be transformed into vector polygons. These vectorized floor plans are then consolidated into story plan maps. Multiple story plans are aligned and incorporated with height information to establish 3D building models. The final story plan map contains building number and location, floor polygon, story information and story location. The derived model may be utilized in conjunction with the building attributes including data of land registration, data of building ownership and data of other rights over buildings to enable 3D cadastral building property management. The graphical data and the property rights attributes are directly linked to the National Lands Information System (Chiang 2012). However, the 3D registration is not yet fully integrated into Taiwan's cadastral system.

The present system of the state cadastre and real estate registration in the Russian Federation is based on the 2D representation of objects including land parcels, buildings, structures and additional historical information (Vandysheva et al. 2011a). However, the Russian Federation has also initiated a trend towards a 3D Cadastre. The current cadastral law is quite general, and it neither explicitly mentions 3D, nor does it prohibit 3D volumetric parcels for registration (Vandysheva et al. 2011b). The initial cadastral prototype emphasizes the visualization of 3D information of the cadastral objects as polyhedrons, while a web-based browser solution has been developed. The conceptual 3D cadastre model is based on the ISO 19152 Land Administration Domain Model (LADM). The model was adapted to the Russian environment and oriented to five types of property: land parcels, buildings, premises, structures and unfinished construction projects (Vandysheva et al. 2011a).

In the Netherlands, 3D cadastre research has continued for more than a decade. Until now, there is no legislation and legal framework concerning the 3D aspect. However, there are several projects underway between government bodies and universities for the implementation of a 3D cadastre and the required legislation. After the development of various prototypes and detailed analyses of various complex cases of uncertainties, the Dutch Kadaster is currently implementing a 3D cadastre solution (Stoter et al. 2012). Several research publications show that the registration and publication of rights on multi-level property is possible within the existing system in the Netherlands. A major achievement is the first 3D cadastral registration of multi-level ownership rights reported by Stoter et al. (2016). Stoter described the registration of a 3D PDF in the Dutch Kadaster, accompanied by the corresponding rights, restrictions and responsibilities. This PDF constitutes a 3D representation/visualization of rights and is an important achievement for the future implementation of a 3D cadastre.

These cases do not constitute the only examples of 3D cadastral system implementation. Other approaches have been implemented in Spain (García et al. 2011), Bahrain (Ammar and Neeraj 2013) and New Zealand (Gulliver 2015). Therefore, the development of a 3D cadastral system may be moved from a theoretical to a practical level, as long as there is the appropriate legislative and technological infrastructure supporting the required procedures and functions.

3 3D VGI and geovisualization approaches

Over the last 20 years, the automatic 3D modelling of buildings has been a major research focus. 3D data acquisition is a costly and time-consuming process, but, at the same time, it is one of the most important aspects of a 3D reconstruction procedure. In recent literature, the currently explored 3D data sources include Lidar data, aerial, terrestrial or spaceborne optical data, topographical data, terrestrial laser surveys, data derived from volunteered geographic information (VGI) and crowdsourced data. In the last decade, various surveys have been developed in order to exploit the potential use of VGI or crowdsourced data in 3D reconstruction procedures, individually or in collaboration with existing conventional data sources. The VGI or crowdsourcing approach poses additional challenges in 3D modelling, because such data are not recorded according to specific photogrammetric or technical requirements. Hence when using VGI data in 3D modelling, there may be a certain trade-off between cost and quality. A wide range of amateur digital cameras, such as those available in today's smartphones, include an economic, consumer-grade single-frequency GNSS receiver. In the future, further sensors like barometers, stereo cameras, laser metres and small laser scanners will be included in a much wider range of smartphones, making them a multi-sensor-system more appropriate for 3D-VGI applications. Thus, 3D data acquisition becomes possible for a wider audience such as general citizens. Among the several different approaches for 3D data capturing and modelling, three (3) discrete categories can be distinguished: the photogrammetry-based approaches; the planning-oriented approaches and the direct measurement-based approaches.

3.1 Photogrammetry-based approaches

In recent years, several methods for building detection, recognition and reconstruction have been developed. In the current literature, reconstruction methods can be divided into three general categories based on the degree of the contextual knowledge, such as: a. model-driven approach (parametric modelling), b. data-driven approach (nonparametric modelling) and c. hybrid approach (Gkeli et al. 2017a, b, c). Many researchers have suggested several different modelling approaches to investigate the potential use of VGI data in 3D reconstruction procedures. The images captured today through smart devices, image sharing sites and social networks, such as Flickr, Instagram, Panoramio, Picasa and Pinterest, have become some of the best known VGI resources, and their potential in the creation of 3D models has been explored (Fig. 1) (Hartmann et al. 2016; Hadjiprocopis et al. 2014; Somogyi et al. 2016). Hartmann et al. (2016) proposed a method for the creation of geo-referenced 3D models using images from Flickr, as that has been the major data source for crowdsourced photogrammetry. Using the VocMath method (see Havlena and Schindler 2014), the data sets are divided into smaller clusters. Each cluster provides the set of images from each camera pose. The individual reconstruction of clusters is performed through a structure-from-motion (SFM) algorithm, while a coarse absolute orientation is performed by exploiting the GNSS coordinates from the EXIF headers of the images. Finally, the geo-referenced 3D model is derived after fusing all available information.

Jeong and Kim (2016) proposed a planar fitting-based semi-automatic reconstruction process, using smartphone images. They developed a mobile application for Android, which supplies the user with additional tools in order to appropriately edit the data and produce the 3D model of the object captured. The application requires that the user obtains two images of the exterior of the target building from two different perspectives, with a sufficient overlapping part. The user is asked to identify the boundaries of the region of interest (ROI) on the mobile device screen. A 3D surface is estimated for each building side. Then, the estimated 3D surfaces for each building side are adapted to the surfaces of a cube in order to reduce gross errors. Zhang et al. (2016) proposed the combined use of aerial-borne LiDAR point clouds and ground image point clouds generated from smartphone images. The main objective of the proposed procedure is the complete reconstruction of a building describing both rooftops and façades using the region growing method. Thus, 3D data capturing through images from mobile devices may constitute a valuable source, as it can operate as a stand-alone or an auxiliary solution for the collection of three-dimensional geometric data.

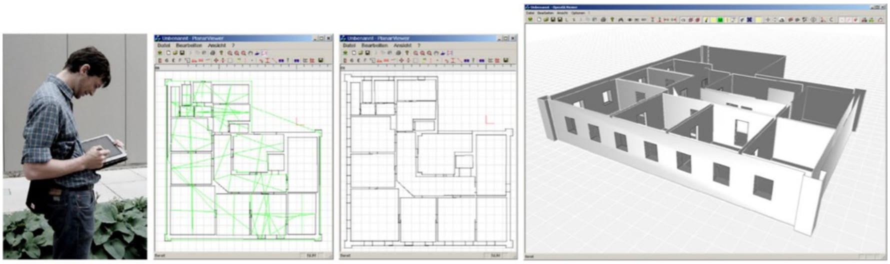
3.2 Planning-oriented approaches

As 3D building models are an enriched version of traditional 2D building plans, there is a direct connection between them in terms of geometry and topology. 3D data acquisition may be done utilizing 2D plans together with adequate height information. Traditionally, the initial phase of a surveying project is the creation of a sketch that presents the necessary measurements, topology and geometry of the

Fig. 1 Reconstruction of the Lion on the Chain Bridge in Budapest, with the camera positions and orientations (Somogyi et al. 2016)

scene. In the same way, 3D data acquisition can be based on a sketch depicting the necessary 3D measurements together with other information about the scene. This information may be about a constraint, a right of a property or other information that describes the main status of the scene. Donath and Thurow (2007) propose a concept for the step-by-step computer-aided capture and representation of geometric building data (mainly the interior space) in the context of plan-oriented building surveying. Data capture is done gradually following a "from sketch to detail" approach. The proposed concept starts with the creation of a non-scaled sketch, presenting the arrangement of rooms, their surfaces and the external surfaces of the building. During this process, the acquisition of information about semantic structures, as differentiated in walls, floors and ceilings, or even other information about the surfaces, such as material, appearance, damages, etc., may be recorded. For the recording process, a touch pad with a pen and appropriate sketch software may be used, such as the commercial software of SketchUp (Sketch Up 2018). Next, the sketch model can be dimensioned using a series of key distance measurements (Fig. 2b, c). After a computational adjustment, this results in a correct geometric model that can be viewed in 2D-mode or as a 3D-model with standard room height (Fig. 2d). Donath and Thurow (2007) note that it is possible to accelerate the surveying process and keep the costs low by utilizing a number of geometric abstractions and reducing the geometric precision.

A similar approach is presented by Ellul et al. (2016) for the identification of 3D ownership situations. The research team sketched a total of 96 possible configurations of land and property ownership combinations. The proposed procedure includes the development of a web-based application that was intended to be used by the general public for the identification of the different land and property ownership situations. The user of the application is asked to select his/her situation from several groups including different types of land ownership. In more complex cases, the user is asked to answer some declarative questions or provide a file or photograph depicting the current situation. The initial approach of such a VGI application resulted in positive feedback from Coimbra Municipality. However, a number of related avenues still remain to be explored in order for this 3D cadastral application to be operational. Clemen and Gruendig (2009) describe a redundant data structure



(a) (b) (c) (d)

Fig. 2 Example of a manually measured sketch survey. **a** Sketch with touch pad **b** sketch tool with distance measurements **c** adjusted model after computational adjustment and **d** 3D view of a geometry model using the tool "OpenGLviewer" (Donath and Thurow 2007) for completing 3D building surveys. The proposed procedure starts with a sketch defining the topology and geometry of the building structure. After the sketching, the measurements are added to a least-squares adjustment in order to derive the best-fit solution.

Other planning-oriented approaches refer to already existing plans in vector format describing the structure of the object being studied. In these approaches, the main interest focuses on the whole building unit, with not much attention paid to the interior structure arrangement of each floor. During the past few years, the scientific community has proposed several different algorithms and techniques aiming to achieve a successful 3D building model; such algorithms have been developed even by non-photogrammetrists. Thus, each volunteer or citizen may be defined as a potential neo-photogrammetrist (Leberl 2010), who can collect, process and store data in order to create 3D models of the real world. The field of VGI has attracted a growing interest resulting in the development of a large amount of 3D real-world applications. Existing 3D-VGI applications mainly utilize model-driven parametric approaches to building models. Eaglin et al. (2013) proposed a different approach by exploiting the power of mobile devices in terms of VGI and 3D reconstruction of the real world. The proposed system was based on a client–server architecture, where users may create, submit and vote on 3D models of the inside building component. The mobile application allows users to create geometry (such as chairs, tables, etc.) through a simplified toolset and editor using parametric modelling, which comprises a different approach compared to the above-mentioned approaches.

Over et al. (2010) investigated the potential use of OpenStreetMap data (OSM 2016) in creating a 3D virtual world, with the result that OSM data are very promising and fulfil the requirements of CityGML LOD1 (Gröger et al. 2008). Goetz and Zipf (2012) proposed a framework encoding OSM properties with CityGML classes for the automatic VGI-based creation of 3D building models as a standardized CityGML model (Fig. 3). The investigation concluded that it is possible to create LOD1 and LOD2 but not LOD3 and LOD4, due to the absence of an automated algorithm for managing imported errors. Over the years, several projects have appeared that generate and visualize 3D buildings from OSM, such as OSM-3D, OSM Buildings (OSM Buildings 2017), Glosm, OSM2World, KOSMOS Worldflier, etc. The main disadvantage of these projects is that buildings are modelled mainly at a coarse level of detail, with the only exception being the OSM-3D project in which a number of buildings are modelled in LOD2 if there are indications of their roof types. The integration of more detail is conducted usually manually (LOD3/LOD4) using other sources via open building models (OBM) (Uden and Zipf 2013), which

Fig. 3 Levels of detail (LODs) as defined in CityGML (Biljecki et al. 2016)

is a web-based platform for uploading and sharing entire 3D building models (Fan and Zipf 2016).

More and more ideas for collaboratively capturing 3D geodata and producing 3D Geovisualizations of several real objects (buildings, etc.) are being discussed by developers. One of the most prominent examples of 3D VGI Geovisualizations is Google 3D Warehouse, which consists of a shared repository that contains user-generated 3D models of both geo-referenced real-world objects, like buildings, and non-geo-referenced prototypical objects, such as street and interior building furniture. Google 3D Warehouse requires a user with a certain level of 3D modelling skill in order to voluntarily contribute (Uden and Zipf 2013). A few years ago, Microsoft Virtual Earth and Google Earth integrated VGI and crowdsourcing techniques in their projects. 3DVIA (Virtual Earth) and Building Maker (Google Earth) provide a model kit to create geo-referenced 3D building models, by exploiting a set of oblique or birds-eye images, in order to derive 3D geometry. These two projects refer to people who do not have photogrammetric skills, but still want to contribute (Fan and Zipf 2016). Given the fact that the above-mentioned projects are far from been open source or open data, it is noted that there are several free-to-use 3D object repositories on the internet, such as OpenSceneryX6, Archive3D7 or Shapeways8, whose contents usually lack connection to the real world but may be useful in enriching real 3D city model Geovisualizations (Uden and Zipf 2013).

3.3 Direct measurement-based approaches

With the rapid development of technology, an increase in the number of consumer mobile devices has prompted development of either 2D or 3D mapping applications describing both the interiors and exteriors of buildings. In the literature, there are several commercial or freely available solutions, concerning a wide range of applications. A really successful mapping mobile application for both IOS and Android mobile devices is MagicPlan (Sensopia MagicPlan 2018). The user can measure room dimensions in real time, capturing 3D information. MagicPlan lets the user create dimensioned floor plans without actively measuring or drawing through innovative algorithms and Augmented Reality technology. To estimate room measurements, the user must interactively mark floor corners in an augmented reality view. While MagicPlan algorithms are proprietary and unpublished, they can estimate and use the height of the observer, i.e. the camera of the mobile device, and the tilt in order to estimate the scene depth. Thus, a coherent floor plan is created, depicting all the appropriate geometric data, and it can be used for the creation of the corresponding 3D model of the building space using a data model such as CityGML, which has been designed for defining and exchanging 3D urban information. Sankar and Seitz (2012) proposed a system based on measurements derived from smart phone devices. The proposed application can easily capture, visualize and reconstruct homes, offices and other indoor scenes. The application leverages data from smartphone sensors such as the camera, accelerometer, gyroscope and magnetometer in order to derive the 3D model of the scene and construct 2D floor plans. All the measurements follow the Manhattan-world environments assumption and rely mainly on angular data. However, as with all experimental solutions, there are some discrepancies that must be investigated, such as inserted errors due to the wall thickness.

Rosser et al. (2015) proposed a different approach using an interactive mobile tool that allows users to measure the interior space of a building. Using the mobile application, the user can navigate through a floor of a building and make the adequate measurements. The individual representations of each building room are assembled within a precise building outline in a plan view on the mobile device. The system performs spatial adjustments in accordance with soft and hard constraints imposed on the building plan geometry and room measurements. Using the appropriate constraints, derived accuracy is simultaneously improved, resulting in accurate interior plans from imprecise measurements. Then, building plans may be used to generate extruded 2.5D building models. The experiment shows that the achieved average accuracy can reach 0.24 m, close to the 0.20 m recommended by the CityGML LoD4 specification (Rosser et al. 2015). Jamali et al. (2015) have investigated several techniques for indoor 3D building data acquisition. In order to reduce the cost and time of the data acquisition process, they used a Trimble Laser Ace 1000 range finder. A range finder can be considered as a basic mobile total station with limited functionality and low accuracy, which mainly measures distances. Using this system, a survey of the interior of a building was conducted. Finally, the geometry of the rooms had several deformations as the conducted measurements are not as precise as a laser scanner or total station measurements (Fig. 4). For this reason, the range finder was calibrated using a least-squares adjustment algorithm. Jamali et al. (2015) believe that the proposed approach may not reach high accuracy requirements but can be employed for basic indoor modelling in order to minimize the cost and time requirement of 3D city modelling.

In the available literature, there is a wide range of different approaches concerning 3D data acquisition procedures and post-processing. Some of them favour the

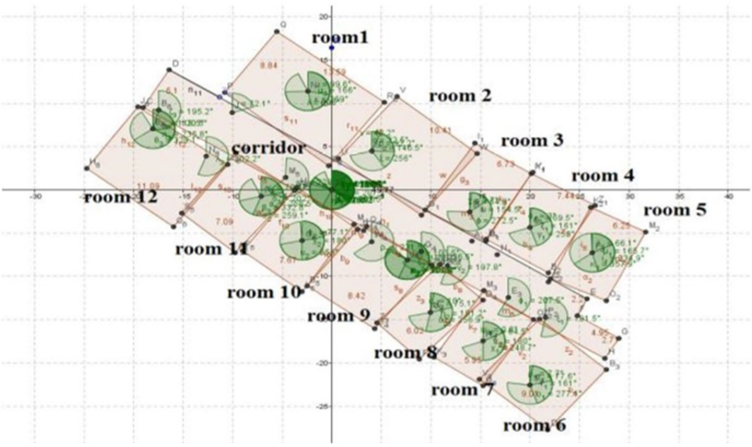


Fig. 4 Generated floor plan by Trimble LaserAce 1000 (Jamali et al. 2015)

acquisition of 3D geometric information interactively, utilizing data from images or laser scanners. Others favour the acquisition of 3D geometric information directly with distance or height measurements together with a plan depicting the geometry of the object or the scene of interest. The latter examples are usually accompanied by semantic information concerning the object of interest. In both cases, the type of data acquired (geometric or semantic information) varies depending on the specific application. Utilizing appropriate changes, each of the approaches may adapt both geometric and semantic information in order to serve the main objective of an application. Thus, in the case of a 3D cadastre, an appropriate approach can enable the capturing of both geometric and cadastral information concerning the property, the property rights, any restrictions and responsibilities.

4 Proposed crowdsourcing framework for 3D cadastral surveys

The main components of the proposed framework are the rights holders' active participation, the exploitation of modern IT tools, m-services and the development of an innovative 3D reconstruction algorithm for automatic 3D modelling and visualization of the main entities of a 3D cadastre, which are the individual property units. The proposed procedure represents the most expensive and time-consuming phase of the implementation process, which is the 3D cadastral data acquisition including the semantic information of the ownership status and other rights, as well as the 3D modelling and the visual representations of the property units. As the legislation and the cadastral surveying procedure differ from country to country, in this approach a flexible framework is introduced in order to save time and funds, and to provide a fast and inclusive solution for the initial implementation of a 3D property registration. The proposed framework is depicted in Fig. 5.

In a "parcel-based" land administration system, property rights and responsibilities refer to the land parcel and to the building. In established and well-functioning 2D cadastres, the land parcel unit and the building footprint are already registered and included in an updated cadastral map. In areas with incomplete cadastres, a digital 2D cadastral map update must be recorded first. In the latter case, the land parcel boundaries as well as the building footprint may be identified on the available basemap, which may be, e.g. a true orthophotograph, an aerial photograph or even OpenStreetMap according to the budget available. For this purpose, the utilization of a crowdsourced 2D cadastral survey approach, in order to collect such data, may lead to an effective solution both in developed and developing countries. As has been shown in earlier publications, the determination of land parcel boundaries and building footprints may be easily conducted by the rights holders identifying and digitizing them on the available basemap that will be available on their mobile phone screen (or laptop, or tablet) (Mourafetis et al. 2015; Apostolopoulos et al. 2016; Gkeli et al. 2016).

The proposed crowdsourced 3D procedure starts with the declaration of a specific area under cadastral survey. The NCMA should provide a recent basemap for the compilation of the necessary 3D cadastral survey. As the available geospatial infrastructure differs from country to country, the selection of the appropriate basemap is

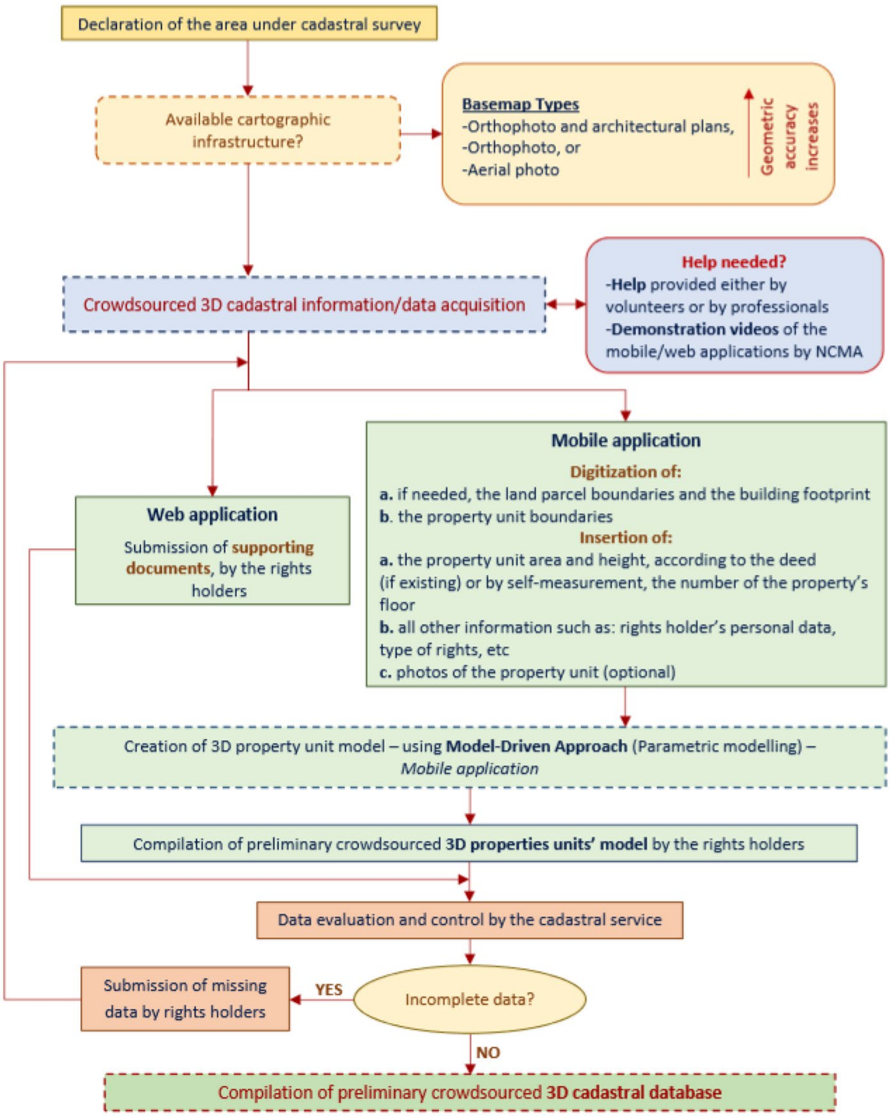


Fig. 5 Proposed crowdsourcing framework for the initial registration of 3D cadastral data

crucial and should be based on the options available for each country. The 2D cadastral map, including building footprints and an overlay of the architectural plans of the units, is the best option to proceed with the 3D recording. If not available, a very large-scale orthophotograph will help to provide the 2D cadastral map by digitizing the parcel boundaries and the building footprints using crowdsourcing methodology. Thus, geometric accuracy that meets specifications can be ensured (Mourafetis et al. 2015). Architectural plans should then be matched with the digitized building footprints. In the absence of architectural plans or/and orthophotographs of high accuracy, horizontal plans of each floor of the building made by the rights holders showing the individual property units and an orthophotograph of less accuracy, or even an aerial image, may be used instead, thus reducing the geometric accuracy significantly. The land parcel boundaries and the building footprints should be visible on the orthophotograph; this is usually the case in urban areas where boundaries are fixed on the ground and this obviously increases the accuracy of digitization; if the parcel boundaries are not readily visible, the GPS sensor of the mobile phone should be used to digitize the land parcel boundaries. Other methodologies may also be used (Gkeli et al. 2016).

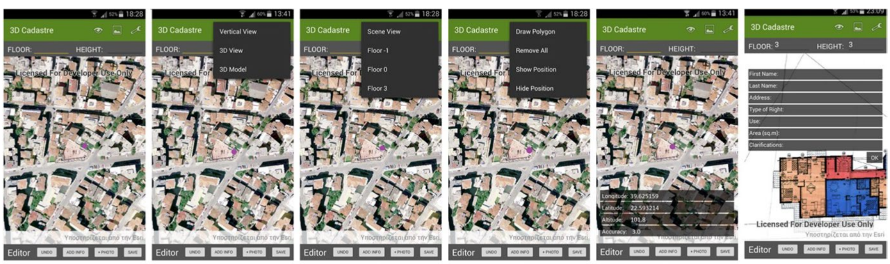
In the next phase, the holders of rights will be asked to submit the boundaries of the individual property units (condominium) for which they have rights, together with photos or files of all available legal documents proving their rights. The NMCA should provide the rights holders/citizens with a mobile and a web cadastral application capable of supporting 3D cadastral surveys. Mobile applications and wireless services are inclusive and preferable as not everyone has access to a cable internet. Moreover, the mobile application allows the rights holder to move throughout the property using the GPS sensor of the mobile device in order to collect directly the necessary information/measurements. As shown in Mourafetis et al. (2015), the achieved accuracies using the GPS sensor of mobile phones are high in urban areas, due to the dense network of antennas; minor corrections can also be achieved by moving the cursor. Thus, in the proposed framework, a mobile cadastral application may be utilized for the acquisition of basic 3D geometric and descriptive cadastral information. Through the mobile cadastral application, the identification of the property boundaries on the available basemap may be done by the rights holders and/with the support of team leaders or other non-professional assistants following brief training. Simultaneously, the holders of rights may submit information about the property: unit height, the area according to the deed (if existing) or by self-measurement; the number of the floor on which the property unit is located; other information, such as rights holders' personal data and type of rights; and verification images (photos) of the property unit (optional). This declared information represents the fundamentals for the automatic 3D modelling of each property unit through the mobile cadastral application. With the determination of each property unit boundaries, especially in cases of multi-story buildings where multiple properties exist, information about the building interiors is also revealed, leading to a real 3D representation of the buildings and not just a 2.5D representation.

NCMAs should support citizens with adequate demonstration videos, detailed instructions on how to use both applications, as well as locally trained volunteers/team leaders and local professional surveyors to act as team leaders in order to help the rights holders to complete the declaration. (This can also be an e-training course provided by the NMCA.) An example of a similar mobile cadastral application that supports 2D crowdsourced cadastral surveys is the BoundGeometry application, which was developed by the authors and successfully used in various areas of interest (Apostolopoulos et al. 2016; Gkeli et al. 2016). Following a similar concept, a mobile application on Android, capable of 3D data acquisition and 3D parametric modelling, is developed and presented in Sect. 4.1 for the initial implementation of 3D property registration. The main purpose of the mobile application is to provide an easy solution to the user in order to automatically produce and visualize 3D semantically enriched property unit models, located above or below the ground surface, by inserting the appropriate geometric and descriptive information through the mobile application. Subsequently, the electronic submission of supporting legal documents and additional evidence about the rights and rights holders may be conducted through a cadastral web application. By the completion of this phase, the NCMA will have a draft 3D building and property unit database conducted by the rights holders. The evaluation and control of this database may be carried out by the cadastral agency and through publishing the collected data, or it may be outsourced. Additional data, together with the collection and submission of any objections for corrections identified by the rights holders in the initial data, should be accepted.

Certainly, the combined use of a web and mobile application does not constitute the only effective solution capable of supporting the 3D data acquisition procedure. The submission of the legal documents and additional evidence about the rights and rights holders may be done directly through the mobile cadastral application by attaching them either as scanned documents or as photos. Especially in countries where the technological infrastructure is limited, the exclusive utilization of a mobile application is considered to be an inclusive and preferable solution, as not everyone has access to wired internet. Therefore, the option(s) of the application(s) for the proposed crowdsourcing framework for 3D cadastral surveys varies and may be adjusted according to the current needs and the available infrastructure of each country.

4.1 Crowdsourcing mobile application for 3D cadastres

To support the proposed framework, an open-source prototype for Android mobile devices is developed by the authors (Fig. 6). The application assists the proposed procedure for the implementation of 3D Cadastres, as it may be utilized for the collection of 3D-crowdsourced information by the holders of rights or other non-professionals; for the automatic generation of 3D property unit models as block models



(a) (b) (c) (d) (e) (f)

Fig. 6 Overview of the developed application supporting the proposed crowdsourcing procedure for initial registration of 3D cadastral data. **a** The mobile application's user interface **b** tools for adjusting the viewing mode of the scene **c** basemap selection tools **d** polygon drawing tools **e** representation of GPS coordinates (Show position tool) **f** representation of input information fields (ADD INFO)

(LoD1), using a model-driven approach; and for their visualization in real time. The mobile application aims to create 3D property units using existing 2D architectural plans while using tools for the identification of the property boundaries on the orthophotographs, and using the digitization procedure and the insertion of the adequate cadastral information about the rights. The mobile GPS device is utilized only for a rough positioning on the orthophotograph in order to avoid gross errors during the rights holder's orientation in 3D space. The collected data and 3D property unit models are stored in the ESRI Cloud (ESRI 2017). For the development of the mobile application, a set of software tools is utilized:

- the Integrated Development Environment of Visual Studio 2013 (IDE);
- the Java Deployment Package, Oracle JDK 8 (Java Development Kit);
- the Android SDK Manager (for API level 19);
- the ESRI's ArcGIS Runtime SDK for.NET (100.0.0) add-in, which adds the function of ArcGIS to the application via libraries (with a wide variety of methods and functions);
- the add-in Xamarin 4.5.0 for Android Support Library, which allows developers to build Android, iOS, and Windows apps within the IDE using code completion and IntelliSense;
- the programming language of C#;
- the ArcGIS Online Server for the storage and management of data.

The application is developed and tested on an Android 4.4 mobile device with a 5.25-inch screen, but it also can be adjusted for other Android devices with different technical characteristics. The mobile application allows the user to browse up to 4 different basemaps using button widgets, depicting either the orthophotograph of the area or the floor plans of each building. This application simulates the 3D real world utilizing a digital terrain model (DTM) offered by ESRI (2017). ArcGIS Online is used to store the data. Data are pulled from the application if there is an Internet connection. The identification procedure reaches high accuracy requirements, as the maximum supported level of scale reaches 1:100. The mobile application utilizes the GPS of the mobile device, receiving continuous updates for the user's position (Fig. 6). In the case that the GPS is inactive, a warning window appears, prompting the user to activate it.

The application provides a set of tools for the identification of property boundaries and the insertion of the necessary proprietary information for the declaration of the property rights. The user/rights holder may define the boundaries of the property upon the basemap by digitizing the corners of the polygonal boundaries on the basemap: first the land parcel property boundaries and then the property unit boundaries utilizing the digitization tool. The user may then insert additional information about the personal information of the rights holder, the type of the property rights to be declared and any additional comments regarding those rights. The data collection procedure requires that the user enter the spatial data values in metres through the "Height" and "Floor" fields, which define the height and the number of the floor on which the property unit is located. The height may be measured with a simple measuring tape from the interior of the property unit or may be assumed to have a default value of about 3 m. Once the data are imported in the application and checked by the rights holder, the 3D property unit model is automatically produced based on the inserted geometric (polygonal) and numeric information (height, floor). The visualization tool should then be selected so that the 3D property unit model will be visualized on the mobile phone screen; the property unit may be located above or below the ground. In addition, the application allows the user to capture photos of the property unit in order to better identify it. Finally, the user can store the collected data in the cadastral database, updating the system with the new records and the corresponding 3D property unit model. Next, the data are presented on the basemap in real time, along with the corresponding 3D property unit model, in 3D view mode of the application (Fig. 6).

4.2 Case study

In order to test the proposed procedure in cases of multidimensional and overlapping property rights, a case study was performed in an urban area of Greece. The test area is the city of Larisa, located in northern Greece. The developed application is tested on a multi-story building in the centre of the city. The recording levels include levels above and below the terrain, making both the process and the results quite interesting. The main objective is to identify the boundaries of each property unit together with some basic descriptive information referring to the ownership by the rights holders (as volunteers). The holders of rights were middle-aged local people of various levels of education and skills, but well informed as to the use of smart phones. After a brief training about the functionalities of the developed mobile application, they were familiar with the application.

When using the developed mobile cadastral application, the rights holders are asked to digitize the boundaries, declare the height and the floor in which their properties are located, and submit information about the property unit. The basic descriptive information concerns the rights holder's personal data (first name, last name, type of rights, etc.), information about the property (address, use type, area size) and additional descriptive information about the property unit, which may be declared by the rights holder. For implementation of the proposed procedure, an orthophotograph of the case study area at a scale of 1:1000 and the floor plans of the underground floor, the ground floor, the first and the third floor at a scale of 1:50, are used as basemaps (Fig. 7). The GPS positional accuracy is about 1–4 m, and is used only to avoid gross errors during rights holder's orientation in the test area. To achieve the required geometric accuracy, the digitization is done using the cursor, moving it manually on the basemap.

The recorded process is conducted by the rights holders using the mobile application. The registration process starts by digitizing the land parcel property boundaries on the basemap. The rights holder then has to identify the property unit boundaries by selecting the floor in which the property unit is located. The selection of the proper basemap is conducted through the selector basemap tool. Then the rights holder has to select features (points) on the basemap, using the digitization tool, in order to form the polygon of the property unit. Next, using the insertion tool, the

Fig. 7 Orthophotograph of the case study area at the scale of 1:1000 (top left) and the floor plans of the underground floor (top right), the ground floor (bottom left) and third floor (bottom right) at the scale of 1:50

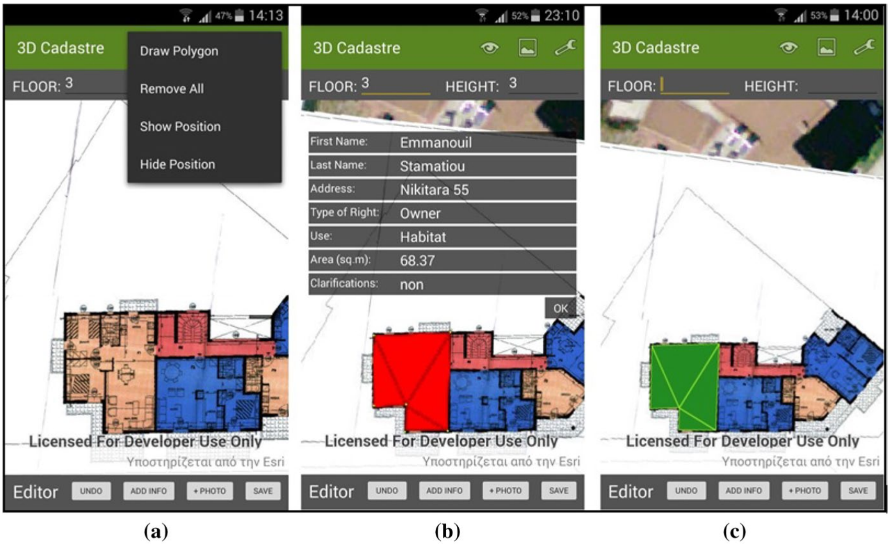


Fig. 8 Example of the recording process on the mobile application, including **a** the selection of the digitization tool **b** the polygon digitization and insertion of the adequate information and **c** the presentation of the declared property unit on the basemap

Fig. 9 3D Visualization of the declared properties (in green) in their absolute position on the ground, using the 3D view tool of the mobile application (color figure online)

Fig. 10 3D Visualization of the declared properties (in green) in their relative position (above and below) with the ground (in red), using the 3D Model tool of the mobile application (color figure online)

rights holder inserts adequate descriptive information regarding the declaration of rights and the rights holder's data. The rights holder is able to check and correct any wrong input and update the information. This procedure is presented in Fig. 8. Once the data referring to each property unit are imported and checked, the 3D visualization tools allow the user to see the 3D property unit model, above or below the ground, through the selection of the corresponding tool (Figs. 9, 10). In the last step of the registration procedure, the collected data are stored in the ArcGIS Online Cloud, updating the system with the new records and the corresponding 3D property unit models.

The overall procedure is relatively quick as the registration of each property lasts about 3–7 min, depending on the complexity of the boundary shape and the familiarity of the user with the mobile application. No major problems occurred during the data collection through the mobile application; the usage of the mobile application is considered to be easy and understandable by the users. The

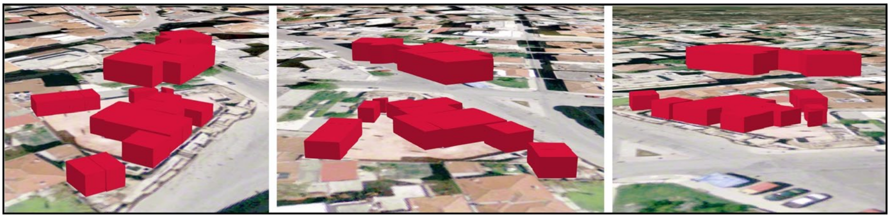


Fig. 11 Visualization of 3D property unit models (in red) in their absolute position on the ground, as they are generated in the ArcGIS Online (color figure online)

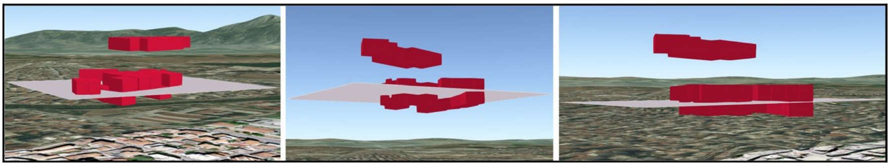


Fig. 12 Visualization of 3D property unit models (in red) in their relative position (above and below) with the ground (in violet), as they are generated in ArcGIS Online (color figure online)

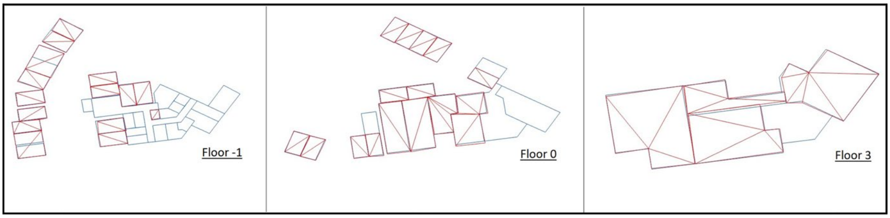


Fig. 13 Comparison between the digitized polygons (in red) and the reference data (in blue), for each one of the studied building floors (color figure online)

existence of an architectural floor plan is really helpful, as it clearly presents the boundaries of each room, leading to successful results. However, a particular difficulty has been identified that is worth mentioning. This refers to errors that may be imported during the procedure, due to the quality of the utilized DTM (digital terrain model). Irregularities such as incorrect altitudes of certain points in the DTM may lead to significant errors during the 3D data collection procedure.

Following the completion of the registration procedure by the rights holders, the results are exported from ArcGIS Online, and the draft crowdsourced 3D property unit models are generated (Figs. 11, 12). The data are then evaluated in terms of accuracy, quality and completeness, through a comparison with the reference data. The plans describing each unit on the floor plans are used as reference data. As the 3D models are generated by a model-driven method based on the footprint of each property unit, the comparison should be conducted between the reference data and the digitized polygons referenced to each one of the building floors (Fig. 13). The evaluation of the results shows that there are no significant discrepancies between the two data sets (Fig. 13). The average accuracy deviation between the two data sets is 0.17 m, while the maximum and minimum deviation is approximately 0.42 m and 0.01 m, respectively. The achieved accuracy is satisfactory, revealing that the proposed registration procedure utilizing the mobile application leads to reliable results. The 3D property unit models are correctly positioned in 3D space, while the small shape defects are caused by the imported errors in the digitization process, but they do not affect the ultimately produced result. The proposed procedure, together with the developed mobile application, has notable potential. As has been highlighted previously (Apostolopoulos et al. 2016; Gkeli et al. 2016) as well as during the brief training of rights holders in the current case study, the results of a crowdsourced procedure may be greatly improved after a proper training and briefing of the volunteers by a trained team leader or a professional surveyor. It is noted that this case study constitutes only a practical example of the exploration of the function and results of the proposed framework. In future research, other alternative scenarios concerning the available basemaps should be checked. Also, a large-scale implementation should be conducted in order to evaluate the proposed framework in more complex cases.

5 Assessment of the proposed crowdsourcing procedure and conclusions

While the traditional 2D cadastre is adequate for provision of information about the legal status of real estate in the majority of cases, some significant gaps in cases of multiple use of space with overlapping and complex property issues are presented. In light of increasing urbanization, this situation will only become more complex as construction seeks to make best use of vertical and underground space on limited land (Ellul et al. 2016). At the same time, traditional cadastral procedures are time-consuming and complicated, resulting in an increasing need for modern approaches for the compilation of cadastral surveys. Crowdsourcing approaches in contrast to traditional approaches for 2D cadastral surveys may more reliable in some places as the responsibility for the initial data collection process is transferred to the rights holders. Gross errors may be reduced as the rights holders can better identify their properties without making assumptions about the property boundaries or the names of the owners (Gkeli et al. 2016; Mourafetis et al. 2015). Furthermore, with the determination of the property boundaries by each rights holder, a double check on the topological and geometric correctness of the declared data is possible, especially in cases of neighbouring property boundaries.

It should be noted that most cadastral systems, even some long existing cadastral systems in developed countries, may need to improve their geometric accuracies in some parts of their jurisdiction. The most common reason is the fact that long existing systems do not usually have a unified geometric accuracy as parts of the country were surveyed in various periods and most of the cadastral diagrams are digitized from the existing analog maps. Using the current tools, such as UAVs, right-holders' participation and mobile applications, it is possible to gradually improve the accuracy as well as completeness—if and where needed—in a fast and affordable manner. Also, maintenance of the systems may be achieved more easily in future by using such tools. This may require some legal amendments, especially if restrictions in using the cloud are in place. However, this is not the case for many countries.

The most important factors for any cadastral project are the required costs and time demands of the overall procedure. Due to the difficulty of implementing traditional cadastral field surveys, the exact time of their completion is uncertain, leading to delays and the gradual increasing of the cadastral procedure's cost. Simultaneously, cost reduction through crowdsourced cadastral data collection is significant, as the greater part of the field work is done by the rights holders. Through such a crowdsourcing procedure, the holders of rights may collect cadastral data utilizing modern technological developments, IT tools and m-services, such as smart devices, etc., reducing the required time and efforts for the completion of traditional field work (Apostolopoulos et al. 2016; Gkeli et al. 2016). The cadastral maps produced through crowdsourcing should be verified by either authorized cadastral surveyors or directly by the cadastral agency, depending on the specific situation in each country. The results from earlier stages of this research are very encouraging (Gkeli et al. 2016; Apostolopoulos et al. 2016; Mourafetis et al. 2015). However, the success of the results depends heavily on the available infrastructure in each country (e.g. orthophotographs for basemaps, dense network of mobile phone antennas, etc.) (Mourafetis et al. 2015). A crowdsourced approach does not aim to produce highly accurate cadastral data, but a reliable, fit-for-purpose procedure with satisfactory accuracy, in an easy, fast and cost-effective way.

As presented in Sect. 2, there are several approaches introducing a 3D cadastre that demonstrate the need for the development of such a system. The main objective of the proposed crowdsourced fit-for-purpose procedure is to support land administration agencies in increasing the efficiency and transparency of land administrative systems in urban areas. Utilization experience derived from 3D city models in land administration procedures provides increased safeguarding of rights while possibly minimizing property conflicts and disputes caused by complex overlapping property rights.

This paper presents an innovative approach for the initial registration of 3D cadastral data, using crowdsourcing techniques. The mobile application presented here utilizes the current algorithms and techniques in 3D reconstruction (Gkeli et al. 2017a, b, c). According to the results of the case study the users did not face any particular difficulty in understanding and using the application, as it was developed for users without a certain level of technical skills. Detailed training about the function of the application was sufficient for users to become familiar with the tool. Adequate demonstration videos and detailed instructions on how to use both applications should also be provided by NMCAs. The recording procedure is relatively fast and was successfully completed with an accuracy of RMS = 0.17 m, while the 3D property unit models are correctly positioned in 3D space, maintaining the user's defined dimensions during the recording procedure. Each 3D property unit model is accompanied by the corresponding semantics/descriptive cadastral information, and thus, the application facilitates post-processing and querying procedures in order to derive several new data useful in the management of land and real estate.

The introduction of VGI and crowdsourcing techniques in land administration procedures have caused several reactions in the research community concerning data quality, reliability and achieved accuracy. However, the basic question should be as follows: Is the achieved quality adequate according to the purpose for which the data are collected? The approach presented here is a fit-for-purpose approach, good enough for managing current land issues within a specific country or region at an affordable cost, rather than simply following advanced technical standards. The quality check of the data may be conducted by a NCMA, which, in this case, can operate as a gatekeeper of the crowdsourced 3D data.

Although the proposed framework seems to be functional, there is another very important factor that needs to be considered. One of the most significant questions for several VGI applications is: How can we motivate citizens to participate in an activity? A significant motivation for citizens to support the proposed procedure is the protection of their property rights, providing a transparent, fast and cost-effective solution for the registration of their rights and real estate in 3-dimensions, with the development of an initial 3D cadastral system. Nevertheless, the participation of citizens may be further promoted and enhanced with the method of "gamification". With this method, incentives may be introduced to citizens to activate their participation in the proposed procedure. Early gamification strategies use rewards for players who accomplish desired tasks, or introduces competition to engage players (Apostolopoulos et al. 2016). Following this strategy, a reward for the rights holders' participation in the cadastral procedure may be, for example, a discount on taxes or registration fees for the most active. This constitutes a strong motivation for citizens, which together with the assurance of their property rights may ensure the smooth, robust and efficient implementation of the proposed framework.

Consequently, the proposed framework is an example of a reliable, affordable, fast, qualitative and easy way for the initial implementation of a fit-for-purpose, well-functioning 3D cadastre, even in developing countries. Depending on the availability of the cartographic infrastructure, the accuracy of the results may vary. In countries where an orthophotograph can be provided, the achieved accuracy of the parcel units is similar to the accuracy of "triple A" 2D cadastres. If the rights holders have floor plans that are compiled by engineers who have constructed the buildings, the achieved accuracy of the 3D cadastre is satisfactory. If floor plans compiled by engineers do not exist, VGI methods may be tested; the geometric accuracy of the final product will be reduced, but it is always an option to improve it at a later stage. What is most important in order to meet the Sustainable Development Goals (SDGs) in time is not the final geometric accuracy of the 3D property unit models, but the completion of the registration of all units and rights as quickly as possible by an affordable and inclusive method, while providing security of rights in the most reliable way according to existing funding.

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