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A technical solution for 3D crowdsourced cadastral surveys

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ABSTRACT

The development of 3D property registration systems is indispensable for the spatial determination of property Rights, Restrictions and Responsibilities (RRR), the sustainable operation of property markets and the safeguarding of ownership in the highly urbanized world. Several developments in computer graphics, 3D modelling and rendering techniques have attracted the growing global interest in 3D cadastre. Since 2012, the Land Administration Domain Model (LADM ISO 19152) is adopted as the international standard for 2D and 3D cadastral data modelling. Developed legal procedures and prototype systems for 3D property rights registration provide interesting solutions for data acquisition and visualization but such approaches are time and cost demanding. In parallel, 2D cadastral surveying procedures have progressed significantly in reducing required time and cost, utilizing crowdsourcing methodology and mobile services.

This paper presents a technical solution under development, aiming to provide the beginning for a new era in the initial acquisition, registration and representation of 3D crowdsourced cadastral data, appropriate for both the developed and the developing world. The proposed solution consists of two complementary parts, the technical framework and the crowdsourced methodology to be followed. The technical framework consists of two interconnected parts, the server-side and the client-side. The server-side refers to the Database Management System (DBMS) where the collected data are stored. The client-side refers to the data capturing tool, which in this case is the mobile device. For the server-side, a prototype system based on model driven architecture practices and LADM is developed; while for the client-side, an open-source mobile application for the acquisition of 3D crowdsourced cadastral data, 3D modelling and visualization of 3D property units as block models (LoD1) on a mobile's phone screen in real-time, is developed.

This research is focused on investigating technical aspects for capturing and integrating data about legal rights on physical objects. Detailed investigation of legal issues is not within the objectives of this research. Two case-studies for testing the proposed technical solution are made. An assessment of the current stage of development of the technical solution is presented. The main conclusions converge that the proposed technical solution has huge potentials for the fast, economic implementation of 3D cadastral surveys as it can produce an accurate and reliable 3D information model, depending on the accuracy of the available basemaps. The developed application is easy-to-use as users may not have the necessary level of 3D modelling skills in order to contribute to the registration procedure.

1. Introduction

Through the ongoing rapid urbanization, several complex constructions as well as multi-dimensional and overlapping property rights have emerged. Traditional cadastral systems are challenged to handle recording, managing and visualizing the spatial extent of the vertically stratified cadastral objects. Fuctional 3D digital cadastral systems are required to increase tenure security, reduce risks, time and costs in land and property transactions and mortgages, improve land use and management of urban areas, facilitate cross-boundary trade and enable poverty reduction. Harmonization, standardization and exchangeability of data are values of great importance for the effective manangment of the various types of rights. Actors such as UN-Habitat, the Food and Agricultural Organization of United Nation (FAO), the UN Committee of Experts on Global Geospatial Information Management (UN-GGIN) and the International Federation of Surveyors (FIG) support and emphasize the existence of these principles (Lemmen et al., 2015).

The Land Administration Domain Model (LADM ISO 19152,

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2012LADM ISO 19152, 2012) offers a formal mechanism for describing cadastral data. Model Driven Architecture (MDA) provides an extensible basis for the development and refinement of efficient and effective 2D and 3D land administration systems. During the last few years, LADM has become the main focus of research in linking the legal and physical counterparts of 3D cadastral objects by utilizing various technologies, application schemas and technical models (CityGML, IndoorGML, BIM/IFC, LandXML, InfraGML, etc.) (Thompson et al., 2016; Kitsakis et al., 2016; Atazadeh et al., 2018; Alattas et al., 2018; Gkeli et al., 2018; Kitsakis et al., 2019; Gkeli et al., 2019). Quite a number of countries are active in developing LADM-based 3D Cadastral Information Models, by extending and adopting the standard to the local situations and ecosystems (Lee et al., 2015; Rajabifard et al., 2018; Gkeli et al., 2019). To meet the 2030 UN Agenda SDGs a fit-for-purpose approach will ensure that both developed and developing countries may appropriately built land administration systems within a relatively short time frame and affordable costs, following international standards (Enemark et al., 2014).

Emerging technologies in computer graphics, affordable modern IT (Information Technology) tools, as well as improvements in hardware technology have stimulated researchers to design, develop and test various applications (Tenedório et al., 2013). The application design based on GIS (Geographic Information System) and database technology provides better organization, access, and updating of global GIS systems such as cadastres. Until now, numerous crowdsourcing and VGI (Volunteer Geographic Information) 2D and 3D mapping programs and real world applications have been developed, leading to interesting and satisfactory results (Gkeli et al., 2018; Apostolopoulos et al., 2018; Gkeli et al., 2016; Fan and Zipf, 2016; Uden and Zipf, 2013; Goetz and Zipf, 2012). Mobile GIS technology extends the recording capabilities of 2D and 3D information, speeding up the registration procedure and ensuring the reliability of the collected data by migrating a huge number of citizens/property owners into the data collection procedure. As the complexity of 3D buildings structure is only known to their residents/occupants, crowdsourcing (Goodchild, 2007a,b) may be the best-fitted solution and the only economically feasible approach for the fast implementation of an effective, efficient and reliable 3D cadastral system, with incrementally upgraded accuracy. The introduction of crowdsourcing and VGI in 2D cadastre has been under investigation for a number of years (Basiouka and Potsiou, 2012a,b; Mourafetis et al., 2015; Apostolopoulos et al., 2018; Molendijk et al., 2018; Gkeli et al., 2016; Rahmatizadeh et al., 2016) with positive results. In the last few years the research has focused on the investigation of the potential use of crowdsourcing in 3D cadastral surveys (Ellul et al., 2016; Jones et al., 2017a;b; Gkeli et al., 2017a,b,c,d; Gkeli et al., 2019) while an attempt to adopt LADM standard in this approach has been made (Gkeli et al., 2018). The first results seem to be promising, providing the basis for the implementation of a fit-for-purpose 3D cadastre.

This paper presents a part of an on-going research project that is aligned with this global effort, aiming to develop a practical technical tool for the future management of 3D property rights mainly in urban areas. Chapter 2 presents background information regarding the technical framework of the proposed crowdsourced solution. Chapter 3 describes the proposed crowdsourced methodology for the compilation of 3D cadastral surveys, utilizing the proposed technical framework. Chapter 4 presents the two case studies and includes information and results concerning implementation tests of the developed system in two multi-story buildings of the National Technical University of Athens (NTUA). Chapter 5 presents an overall evaluation of the proposed technical solution. Finally, Chapter 6 presents the main conclusions referring to the perspectives, the geometric accuracy, the cost, the duration and the reliability, of the proposed crowdsourced solution as a basis for the compilation of a well-functioning fit-for-purpose 3D Cadastre, as well as some thoughts about our future work in this field.

2. Background information on the proposed technical framework

2.1. Technical system architecture

The proposed technical framework aims to exploit the current initiatives of the scientific community and provide a modern LADM-based technical solution for the initial acquisition, registration and representation of 3D crowdsourced cadastral data. This effort aims to enhance the procedure and reduce the cost for 3D cadastral surveys, by increasing citizens' role and participation, and to exploitate the potential use of IT tools, like mobile devices (smartphones or tablets), web services, database management systems (DBMS) services, in combination with low-cost software, for the compilation of the preliminary crowdsourced 3D cadastral database. The primary interest of this work focuses mainly on the geometry and representation of the physical 3D cadastral objects (spatial units), while the detailed study of legal issues is not within the objectives of this research. This section contains an overall description of how all the parts included in the proposed framework work together in synergy.

The main idea of this venture is the development of a technical solution enabling the collection, management, maintenance, storage and updatance of a large amount of data through communicating with an Android mobile application. The main components of this technical solution system are the two complementary sub-systems which may be referred and named as the server-side and the client-side. The server-side refers to the web server and therefore to the Database Management System (DBMS) where the collected data are stored. The client-side refers to the data capturing tool, which in this case is the mobile device. For the purpose of this research a database schema according to LADM specification is generated, in order to support the server-side, while for the client-side an open-source mobile application for Android devices, is developed. The server of ArcGIS Online (ESRI, 2019) was utilized for the storage and management of the collected data. The communication

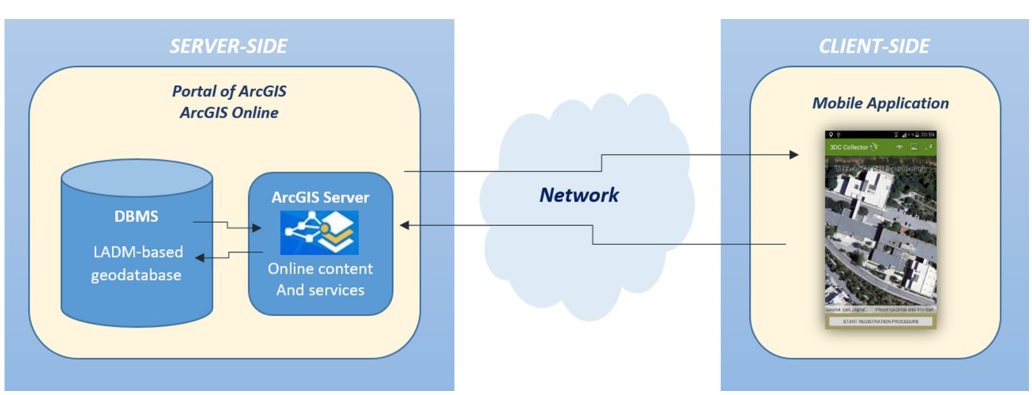

Fig. 1. Server-client system architecture diagram of the 3D cadastre technical framework.

between the server-side and the client-side is achieved through a network connection. An overall diagram showing the server-client system architecture is shown in Fig. 1.

2.2. Conceptual model

For the server-side a DBMS conceptual schema serving the purposes of this research is generated through Enterprise Architect UML modeling tool provided by Sparx Systems (Enterprise Architect, 2019). Enterprise Architect supports the Geography Markup Language (GML) application schemas and the modeling of ArcGIS geodatabases, utilizing Model Driven Generation (MDG) Technologies. The LADM standard is utilized for the generation of the data structure of the database. The geometry of the 3D spatial units, is substantiated with the generation of the new classes: LandParcel3D, LPBaseParcel, LP_BoundaryFaces, LP3D_Points and BuildingUnit3D, BuildingUnit_Top, BuildingUnit_Base, BuildingUnit_VFaces and Points3D, for the description of the 3D land parcel and the 3D building unit, respectively, as it is clarified later on in the chapter. The LADM-based database scheme is developed accordingly so that the final model would comply with the ArcGIS workspace metamodel, which is used by the ArcGIS extension of Enterprise Architect. With the necessary conversions, the final database schema is imported in ArcGIS Pro software where the generation of the final geodatabase is achieved. Subsequently, the ArcGIS platform of ArcGIS Online is selected as the server for the storage of the developed DBMS and thereinafter of the collected data and the relationships among them.

The structure of the developed DBMS supports the 3D aspect of spatial units. According to LADM, a "true" 3D representation of a spatial unit consists of arbitrary oriented faces. However, the identification of the acceptable 3D geometries and representations for the 3D cadastral objects is still challenging (Ying et al., 2015). Despite this fact, we may argue that a real 3D cadastral object may be defined as a valid volumetric object that can be represented by one closed polyhedron refined by a set of connected faces (Ying et al., 2015). A polyhedron may be defined as a 3D solid composed of vertices, edges, faces and an incidence relationship between them (CGAL, 2019). Based on this point of view, the UML (Unified Modeling Language) diagrams describing the structure of the 3D cadastral objects are created.

The developed DMBS schema is based on the main classes of LADM: LA_Party, LA_RRR, LA_BAUnit and LA_SpatialUnit (Fig. 2). A new class named LandParcel3D, is created, to emphasize the basic spatial unit element. LandParcel3D is directly linked to the LA_SpatialUnit class, while an attribute defining the address is added (Fig. 3). The three-dimensional substance of the land parcel is attributed by three new classes: LPBaseParcel, LP_BoundaryFaces and LP3D_Points (Fig. 4). The class LPBaseParcel includes the geometry of a land parcel in 2D, while the class LP_BoundaryFaces includes the geometry describing the polygonal faces of a land parcel. In order to enable and simplify the representation of the land parcels boundary faces in the ArcGIS platform, a KML object (KMLBoundFaceStrings) defining the 3D land parcel is utilized. The class LP3D_Points includes the vertices of the connected polygon faces, preserving the relationships between them. Thus, a 3D land parcel is defined as a set of connected polygonal faces, representing a 3D prismatic volume with no upper and lower bound.

Following a similar concept, a new class named BuildingUnit3D is created, describing the structure of the 3D building units. BuildingUnit3D class is directly linked with LandParcel3D class and it preserves the necessary information describing the structure of the polyhedron geometry of a building unit (property) (Fig. 3). As attributes describing the geometry of BuildingUnit3D class, the number of the floor - where the building unit is located - the height, the area size and the volume of the building unit, are selected. The attribute referring to the current use of a building unit is inserted as a descriptive characteristic. In order to enable and simplify the representation of the building unit's boundary faces in the ArcGIS platform, a KML object (KML_3DBU) defining the 3D building unit volume, is utilized. It is noted that the main interest of this research focuses on the specification of the building units as volumes (LOD1) (Gröger et al., 2008) in the 3D space, so that the individual property units will be registered correctly. A 3D building unit is defined as a set of connected polygonal faces, representing a 3D prismatic volume with specified upper and lower bound. Thus, four new classes are created: BuildingUnit_Top, BuildingUnit_Base, BuildingUnit_VFaces and Points3D, defining the structure of a 3D cadastral building unit. These classes include the geometry describing each one of the building unit's polygonal face - top face, base face and vertical faces - as well as the relationships between them (Fig. 5).

After the completion of the necessary operation for the generation of the database schema, the final database schema is extracted as a Geodatabase Workspace XML Document (containing the ArcGIS schema) in order to be imported into ArcGIS Pro software, and so the cadastral geodatabase be generated. Subsequently, the produced geodatabase is uploaded on ArcGIS Online platform in order to be able to be linked with the rest of the elements of the proposed technical framework.

2.3. Developed mobile application

An open source prototype for Android mobile devices is developed to support the client-side of the proposed technical framework (Fig. 6). Current literature presents a wide variety of crowdsourcing applications available for the collection of mainly 2D geospatial data on Android mobile platforms (Gkeli et al., 2018, 2019). However, cadastral-oriented mobile applications are limited especially in regards to the third dimension. This research domain is newly emerging and may provide promising results for the compilation of a preliminary 3D cadastral database directly by the citizens/rights holders. The developed prototype application is based on the results of earlier stages of the current research (Gkeli et al., 2019, 2018; Gkeli et al., 2017a,b,c,d). The mobile application serves the collection of 3D crowdsourced information by non-professionals; the registration of the cadastral data and their relationships within a LADM-based cadastral geodatabase; the automatic generation of 3D land parcel and property unit models as block models (LoD1), using Model-driven approach; the generation of the corresponding KML objects (land parcel, building unit); and the objects visualization in real-time.

Various programming tools have been analyzed in order to choose the most suitable for the development of the 3D crowdsourced cadastral mobile application. For the development of the mobile application 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 add-in ArcGIS Runtime SDK for. NET (100.0.0) of ESRI, 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 that allows developers to build Android, iOS, and Windows apps within the IDE using code completion and IntelliSense; the SharpKML library; the Server of ArcGIS Online (cloud of ESRI), for the storage and management of data (ESRI, 2019); and the programming language of C# are utilized.

The interface is user-friendly and appropriately configured in order to lead and simplify the registration procedure, while it can be automatically adjusted to mobile devices with varying screen sizes. The developed application simulates the 3D real world utilizing a Digital Terrain Model (DTM) offered by ESRI. The user may be oriented in 3D space utilizing the GPS (Global Positioning System) of the mobile device. It is noted that the GPS of the mobile device is used only for a rough positioning in order to avoid gross errors during rights holder's orientation in the 3D space. As basemaps for the identification and collection of the required geometric data, the available spatial infrastructure (2D architectural plans, orthophotos, aerial photos) may be

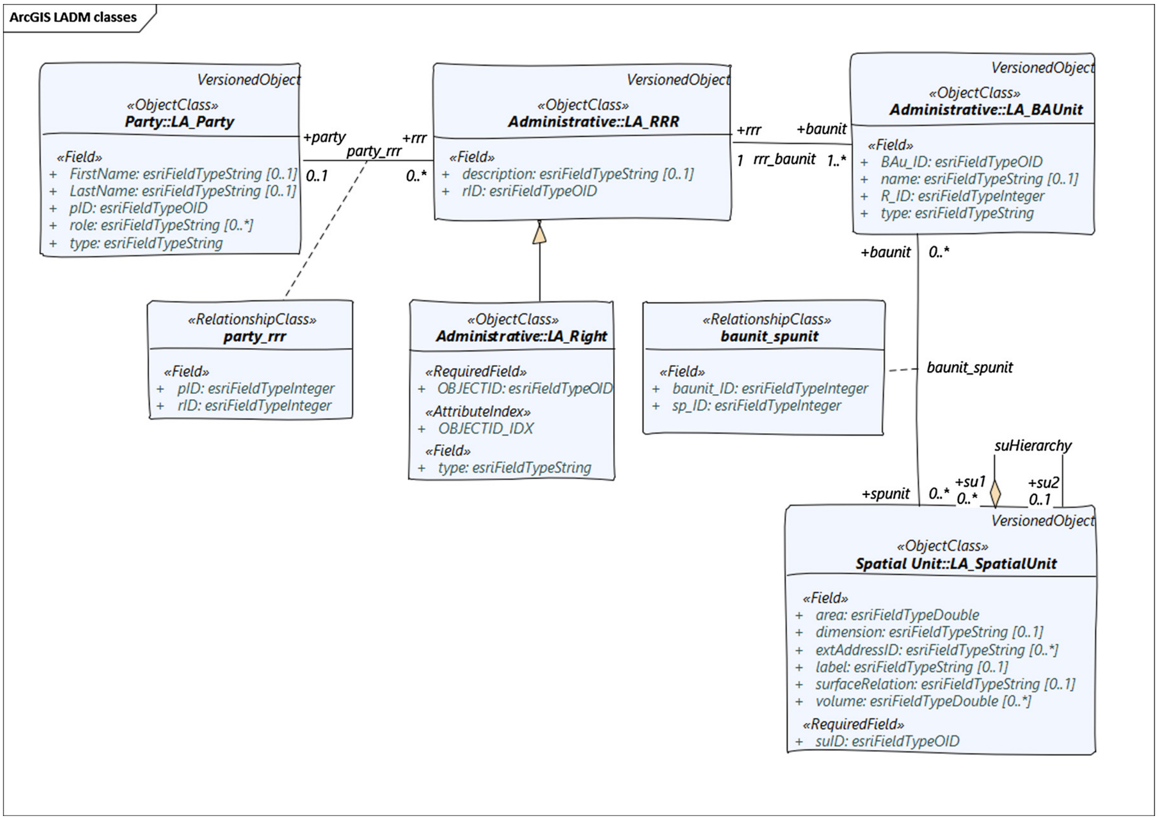

Fig. 2. Conceptual DBMS schema of the developed data model, based on the main classes of LADM: LA_Party, LA_RRR, LA_BAUnit and LA_SpatiaUnit.

utilized. The identification procedure reaches high accuracy requirements as the maximum supported level of scale reaches 1:100. Data are pulled from the application and pushed back into the database in the server of ArcGIS Online if there is an Internet connection available.

The application provides a set of tools for the identification and digitization of the land parcel's and building unit's boundaries on each floor as well as the insertion of all necessary proprietary information (descriptive and geometric) for the declaration of the property rights. In addition, it allows the user to capture photos of the property unit in order to better identify it as well as to attach other available documents (e.g., plans, deeds etc.) proving the respective rights (Fig. 6). The mobile application requires from the user the insertion of the adequate geometric information regarding the structure of each building unit (property). This geometric information corresponds to numeric values in meters that will be entered from the user through the "Height" and "Floor" fields, and 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 user, the 3D land parcel model and the 3D property unit model are automatically produced based on the inserted geometric and numeric information (height, floor). Simultaneously, the respective KML objects of the land parcel and the building unit are generated. Subsequently, by selecting each one of the visualization tools, the 3D property models (land parcel and building unit) will be visualized on the mobile's phone screen, both above or below the ground. Finally, the user can store the collected data in the cadastral database, updating the system with the new records and

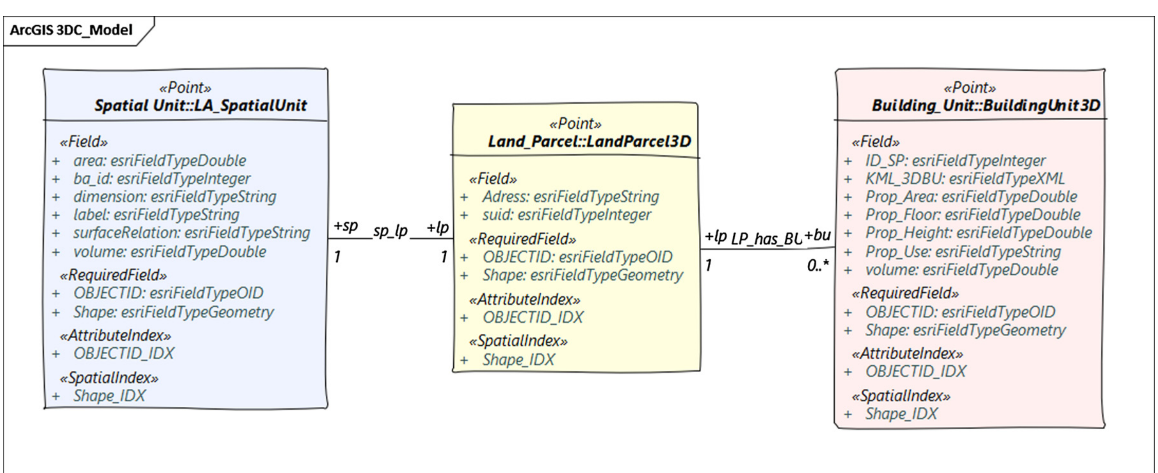

Fig. 3. Conceptual schema defining the relationship between the classes: LA_SpatialUnit, LandParcel3D and BuildingUnit3D.

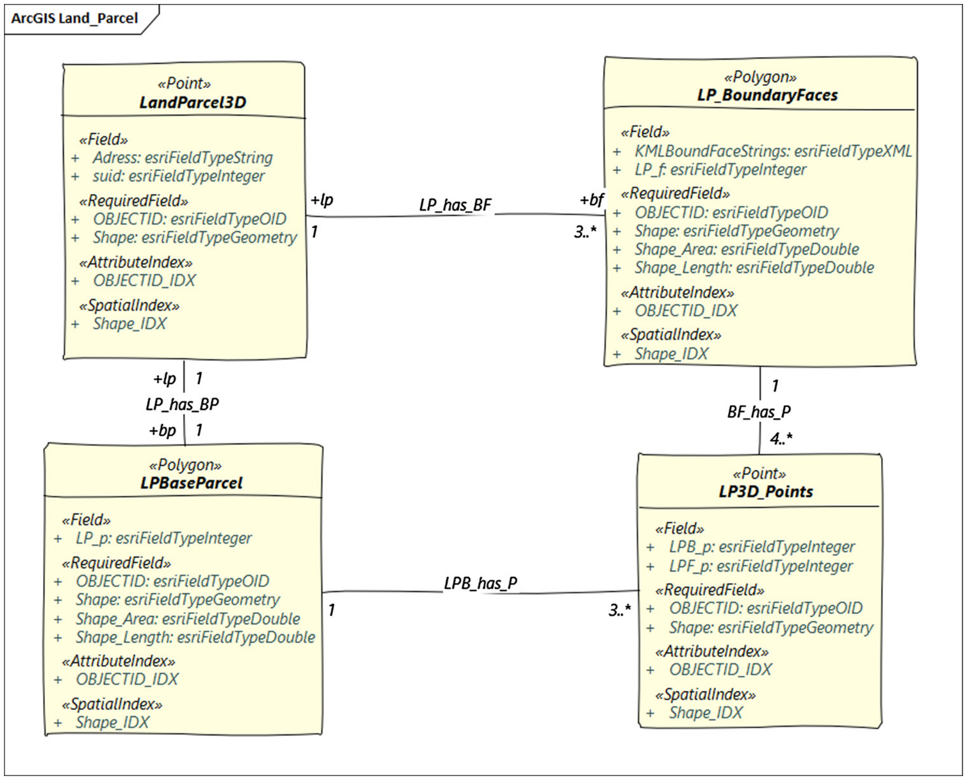

Fig. 4. Proposed conceptual schema defining the structure of a 3D cadastral parcel.

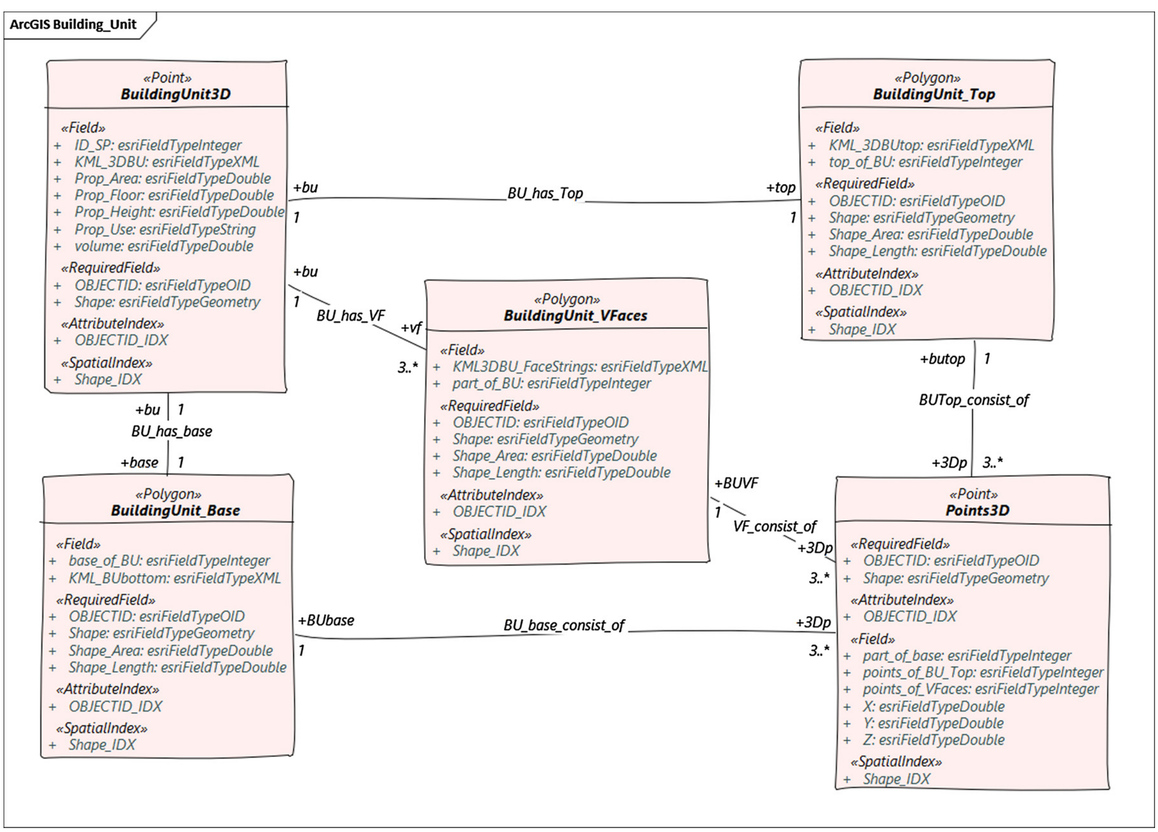

Fig. 5. Conceptual schema defining the structure of a 3D cadastral building unit.

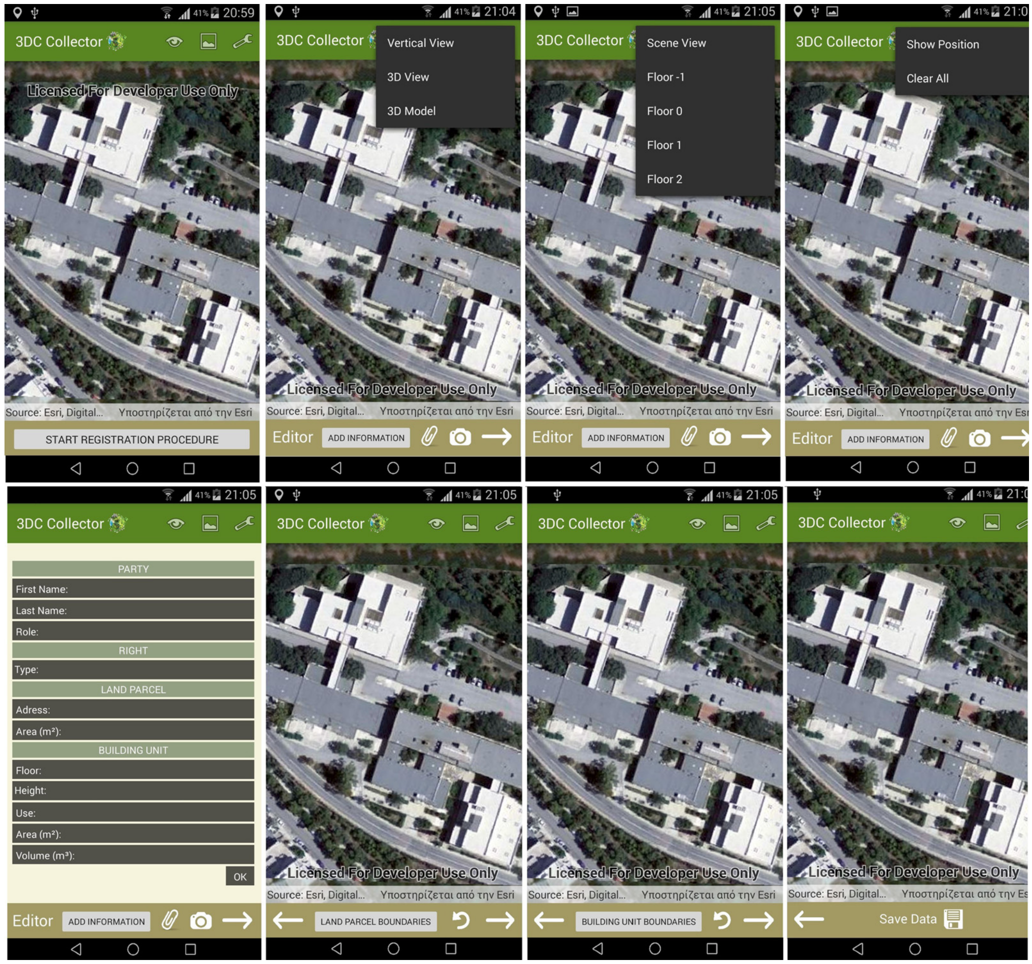

Fig. 6. Users interface overview of the developed mobile application.

the corresponding 3D property unit model, in the server of ArcGIS Online.

3. Proposed crowdsourced methodology

Based on the recent initiatives of the scientific community, on our experience and on the results of our previous research regarding the potential use of crowdsourced data for 3D cadastral surveys (Gkeli et al., 2019, 2018; Gkeli et al., 2017a,b,c,d), we introduce and improve an innovative crowdsourced procedure model for the compilation of 3D cadastral surveys, presented in Gkeli et al. (2018). The proposed methodology relies on the proposed technical framework, providing a fast, geometric accurate, reliable and affordable solution for both the developed and the developing world. It consists of five (5) complementary phases: (i) declaration of an area under cadastral survey by the government; collection of existing geospatial information (aerial photos, orthophotos, existing cadastral information, etc.) and preparation of a draft photogrammetric cadastral map by a professional according to the boundaries that are visible on the orthophoto (optional); assignment of local team leaders to each sub-region by the municipality and the professional, (ii) citizens briefing, motivation and training by the team leaders; promotion of the benefits of the project, (iii) establishment of orthophoto and the draft cadastral map of the area -if existing- as basemap in the app, and collection/correction of 2D data about each plot by the owners/citizens; collection of all available 2D spatial data for the various floors of each building (for this methodology, it is assumed that such plans are available); technical and IT preparation by the team leaders for each multi-story building in collaboration with the manager of each building, (iv) 3D cadastral data acquisition by the rights holders/citizens, and (v) data evaluation, control and submission of the missing data by the rights holders/citizens; compilation of preliminary cadastral maps and data; controls by the professionals; publication of data; objection submission and examination of objections, correction of data, title provision and registration of titles, by the cadastral agency.

The underlying rationale of this methodology is the active co-operation between professionals and citizens. This effort aims to save time and funds required for the compilation of the 3D cadastral surveys, as well as to simplify one of the most important phase of the implementation process, that is the 3D cadastral data acquisition including the semantic information of the ownership status and other rights. The exploitation of the proposed technical framework within this crowdsourced methodology, allows the effective management of the collected data through an automatic process; the construction of the valid 3D cadastral objects; and, finally, the creation of a preliminary 3D cadastral database, based on LADM standards. The proposed methodology is shown in Fig. 7.

The proposed crowdsourced 3D procedure begins with the declaration of a specific area under cadastral survey and the preparation of the basemap to be used for 2D cadastral data collection. The responsibility for the initial collection of the cadastral data is transferred to the citizens/rights holders, reducing gross errors; it will be helpful if a professional collects all existing cadastral information and integrates it with the orthophoto; in some cases a professional may also try to predict the parcel structure according to what boundaries are visible. A professional surveyor or a trained volunteer with the role of the team

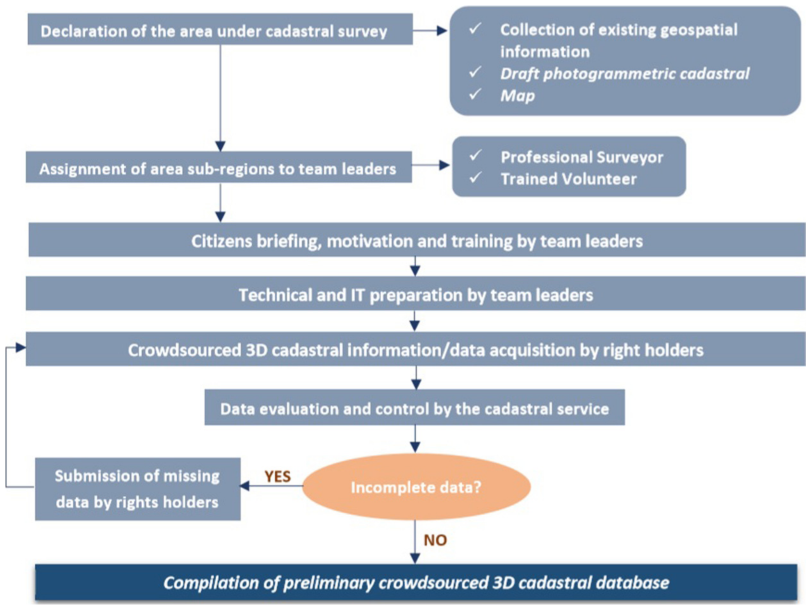

Fig. 7. Proposed crowdsourcing methodology for 3D cadastral surveys up to the stage of the compilation of the preliminary 3D cadastral maps and data.

leader, heads and assists the overall cadastral procedure. The main idea is the existence of several team leaders, each of them may support a sub-region within the whole area under cadastral survey. Through this real-time assistance, the duration of the surveys is being reduced and the reliability of the collected data is being increased.

The second phase of the proposed methodology starts with citizens' briefing about the procedure and the benefits of the cadastral project, by the team leaders. The National Cadastral Mapping Agency (NCMA) should support this process by providing the adequate informative videos and detailed explanatory documents. The citizens may be further motivated and activated through the method of gamification (Apostolopoulos et al., 2018). The NCMA may tempt the community to participate in this crowdsourced procedure by offering an economic incentive such as a discount rate on taxes or registration fees. Such actions strengthen the will for citizens' participation in social processes with a positive impact on its outcome.

The NCMA would be responsible for the development of a LADM-structured database for the storage of 3D building models and the corresponding cadastral information and provide the rights holders/citizens with a mobile cadastral application capable to support the 3D cadastral surveys. An example of such a mobile application is presented in section 2.3. The selection of a mobile application is very helpful as a mobile device allows the rights holders to move throughout the property using the GPS sensor and collect directly the necessary information/measurements regarding their property. Also, the utilization of wireless services in combination with the mobile application, are inclusive and preferable as not everyone has access to a cable internet.

The next step of the second phase includes citizens' training mainly in geometric data capturing matters and on how to use the available cadastral mobile application for the registration procedure. Team leaders should be helping citizens/rights holders to solve any difficulties regarding the provided cadastral software (mobile application) and the type of the data that should be collected, in order to successfully complete the declaration process. In addition, the NCMA would be responsible to support the crowdsourced procedure with the adequate demonstration videos with detailed instructions on how to use the mobile application. The second phase of the proposed methodology is depicted in Fig. 8.

Subsequently, the team leaders should be responsible to gather the available plans to be used as basemaps, such as scanned architectural plans, and to care for the georeferencing of such raster data, and the insertion of these as basemaps into the cadastral server and therefore to the cadastral mobile application. This process consists the third phase of the proposed methodology and is shown in (Fig. 9). As the available geospatial infrastructure differs from place to place and country to country, the selection of the appropriate basemap material depends on the options available in each place/country. A recent orthophoto or even better an orthophoto overlaid with the architectural plans of the building units, is the best option to proceed fast with the 3D property unit recording. In this case, the cadastral information can be classified as Accurate, Assured and Authoritative (AAA) (Williamson et al., 2012; Gulliver, 2015). Otherwise, several other options may be used, such as an aerial photo, but of course reducing the geometric accuracy. In the latter case, the land parcel boundaries and the building footprints should be visible on the basemap. If the parcel boundaries are not visible, the GPS sensor of the mobile phone may be utilized so that they may be digitized on the basemap, or a GPS antenna may be used for more accurate results. A Bluetooth connection of the mobile may be used to connect with the Trimble R2 GPS device (Jones et al., 2017a,b). Of course in some of these cases the achieved accuracies may be reduced.

Next, follows the fourth phase of the proposed crowdsourced methodology (Fig. 10). The rights holders will be asked to collect and submit information concerning the parcel and their property units. Through the cadastral mobile application the identification of the property boundaries (land parcel and building unit) on the available basemaps may be done by the rights holders. Simultaneously, they may submit information about the property: property unit height; area size; the number of the floor (level) on which the property unit is located; other information, such as the rights holder/s' personal data and type of rights; verification images (photos) of the property unit (optional); and legal documents. The submission of the legal documents and additional evidence about the rights and rights holders may be done directly through the cadastral mobile application from the rights holders, by attaching them either as scanned documents or as photos. According to earlier stages of this research, 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 visible on their mobile phone screens (or laptops, or tablets) (Mourafetis et al., 2015; Apostolopoulos et al., 2018; Gkeli et al., 2016). All this declared information is fundamental to the automatic 3D modelling of each property through the cadastral mobile application

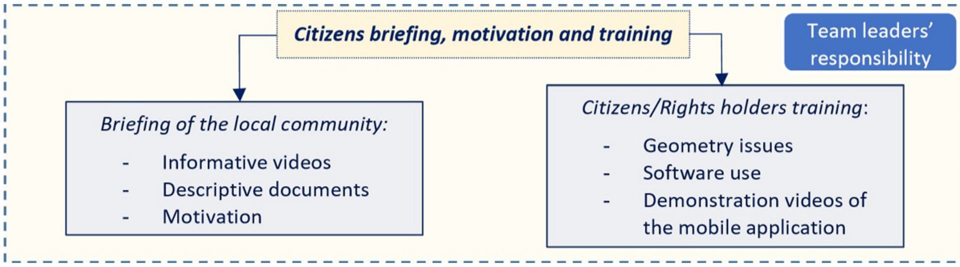

Fig. 8. Second phase of the proposed methodology.

and, finally, generation of a reliable 3D cadastral database. By the completion of this phase the NCMA will have a preliminary land parcel, and the 3D building and property unit database conducted by the rights holders. In the fifth and last phase, the evaluation and control of this database is conducted by cross checking the legal documents with the declared crowdsourced data and through publishing the collected data. This prossess may be carried out by the cadastral agency 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 (Fig. 7). Following the examination of objections and the correction of data, property titles may be provided -if needed- and property registration is compiled.

4. Practical experiment

The developed system was tested for two case studies in two multistorey buildings of the School of Rural and Surveying Engineers of the National Technical University of Athens (NTUA). Our primary interest is to examine the functionality and the potentials of the proposed system, in terms of geometric accuracy, cost, time and reliability. The main purpose is to identify the boundaries of each office room, record some basic descriptive information about the rights and the rights holders, utilizing the developed mobile application on low-cost mobile devices, and record the registration duration for each property. Thus, by cross checking the collected data with the reference data, the main conclusions regarding the geometric accuracy and the reliability of the proposed procedure, arise. Also, by comparing the registration duration and the cost of the utilized equipment with those of the traditional / formal cadastral procedure, some basic conclusions about the time and the cost of the proposed procedure, are exported. In this Section, the accomplished practical experiment is presented, while in Section 5 the assessment of the proposed procedure based on the selected criteria is conducted. It is noted, that the registration process was based on the assumption that the building may be considered as a block of apartments and each office room as an individual property unit.

4.1. Data

As basemaps for the implementation of the proposed procedure, an orthophoto of the test area at a scale of 1:1000 (Fig. 11) and the floor plans of the underground floor, the ground floor, the first and the second floor of each building, at a scale of 1:200 (Fig. 12), were utilized. The recording levels include levels above and below the terrain surface, making both the process and the results quite interesting. For this test the collected data include the land parcels' and each room boundaries, the height of each room, the floor number and the descriptive information about the building (area code, address), the room holder (name, role, type of rights) and the room geometric data (floor, height, use, area size, volume). The parcel boundaries are the boundaries of the NTUA campus parcel. The smartphone's GPS was utilized only for the orientation of the user within the case study area, in order to avoid gross errors, as the positioning accuracy was weak (2 – 6 m), especially in the interior of the buildings.

4.2. Volunteers - training

A team of volunteers is consisted of NTUAs' employees and students, and exploited for the implementation of this practical experiment. The registration procedure is conducted by the volunteers, who are assumed to be right holders. The volunteers are young adult people with advanced digital skills (engineering or technical skills) as they are students from various NTUA Schools and/or young surveyors, and they are well informed about the use of smart phones. After a brief training concerning the objectives of this project and the functionalities of the developed mobile application, they are fully familiarized with the application. According to the proposed crowdsourced methodology, one of the most important phases for the commencement of the registration procedure is the technical and IT preparation, by the team leader. In this practical experiment, as the volunteers may be assumed as potential team leaders, the phase of the technical and IT preparation is conducted in cooperation with them. As the technical part of this application has been implemented utilizing the ArcGIS platform for the management of the data, specific processing steps are performed. After gathering all the available basemaps described in Section 4.1, their

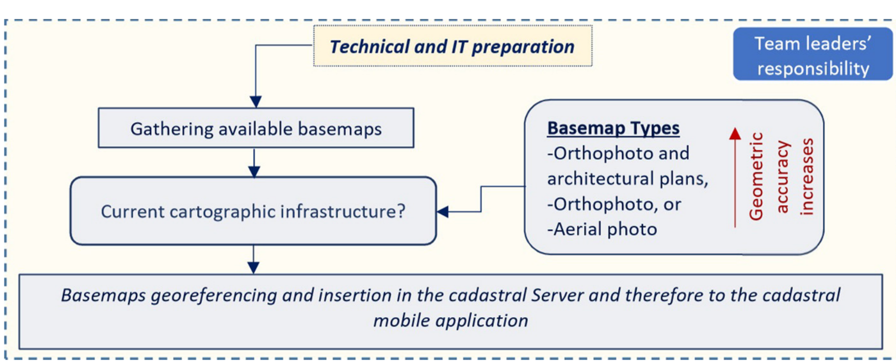

Fig. 9. Third phase of the proposed methodology.

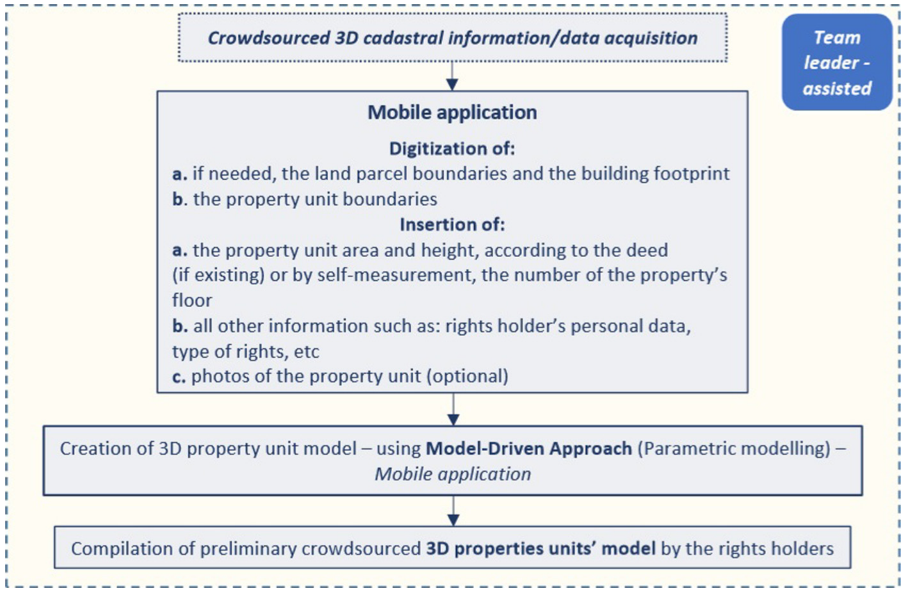

Fig. 10. Fourth phase of the proposed methodology.

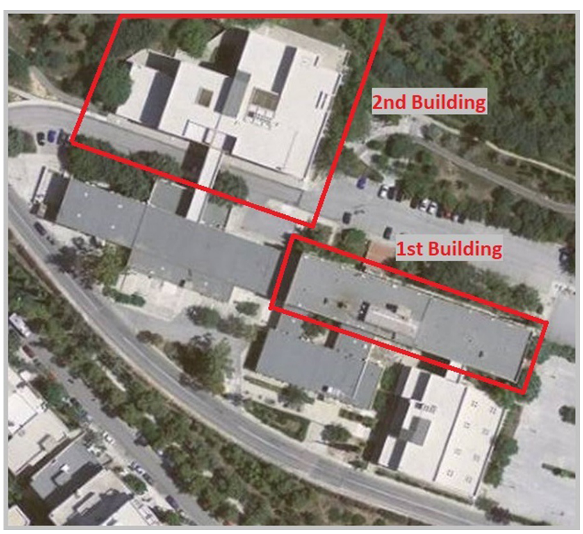

Fig. 11. Orthophoto of the test area at the scale of 1:1000, depicting the studied buildings.

georeference is made using ArcGIS Pro. As the current orthophoto is supplied directly by the NCMA of Greece, it is already georeferenced in the Greek national coordinate system (GGRS87 / Greek Grid). Each one of the scanned raster architectural plans is inserted in the ArcGIS software. Through a polynomial transformation the raster datasets are shifted, from the existing location to the spatially correct location on the orthophoto, which is utilized as reference for the georeferencing process.

Subsequently, the georeferenced basemaps are published in ArcGIS Online as tiled layers. Thus, during this publishing the current basemaps are projected in Web Mercator Auxiliary Sphere projection which is utilized by the server of ArcGIS Online for the projection of worldwide spatial data. Once the basemaps are inserted in ArcGIS Online platform, they may be pulled by the developed mobile application, if there is internet connection available. The developed mobile application is appropriately structured to automatically recognize and pull each one of the basemaps, according to their names in the server of ArcGIS Online (e.g. Orthophoto, Floor_1, Floor_2 etc.). The described process is presented in Fig. 13.

4.3. Field work

In the first step of the registration process the insertion of the adequate descriptive information regarding the declaration of rights and the rights holder/s' data is conducted. Simultaneously, the volunteers/ rights holders may attach images and legal documents (in an official procedure) proving their rights, in order to verify their declaration. In the second step, the identification of the land parcel boundaries is conducted, by selecting features (points) on the parcel basemap (orthophoto) in order to form the parcel boundary polygon where each building belongs (as the cadastral reference area unit / land parcel) utilizing the digitazation tool. Next, the identification of each property unit boundary outline is performed, by selecting the appropriate floor basemap in which the property unit is located, and then by selecting the necessary features (points) on the basemap, forming the polygon of each property unit.

Thus, following this sequence of registration steps, volunteers are able to start and complete succesfully the registration procedure of both case studies, through the mobile application. During the whole procedure the team leader is at the volunteers' disposal in order to resolve any questions that they may have. Fig. 14 (top left) presents the photo of the property unit under registration, and on (top right and bottom) presents a group of volunteers in cooperation with the team leader, during the registation of a meeting room of the School of Rural and Surveying Engineers of the NTUA, while in Fig. 15, the described registration procedure, is presented.

Once the cadastral data are imported, the 3D visualization of the registered room is achievable through the selection of the corresponding tool (Fig. 16). In the last step of the registration procedure, the collected data are stored in the cloud of ArcGIS Online, updating the system with the new records and the corresponding 3D models. The registration procedure is completed succesfully as the necessary information is collected through the mobile application without any major problem. The existence of the architectural plans is helpful as the building unit-boundaries are distinct, increasing the geometric accuracy of the final results. Furthermore, the registration process was fast as the registration of each property lasts about 10 − 12 min (average), depending on the complexity of the boundary shape and the familiarity of the user with the mobile application. It is noted that in this initial practical experement, the" rights holders"/"volunteers" retain some engineering understanding and thus they can better cope with the 3D space, making the results as a sample of the best possible that may be

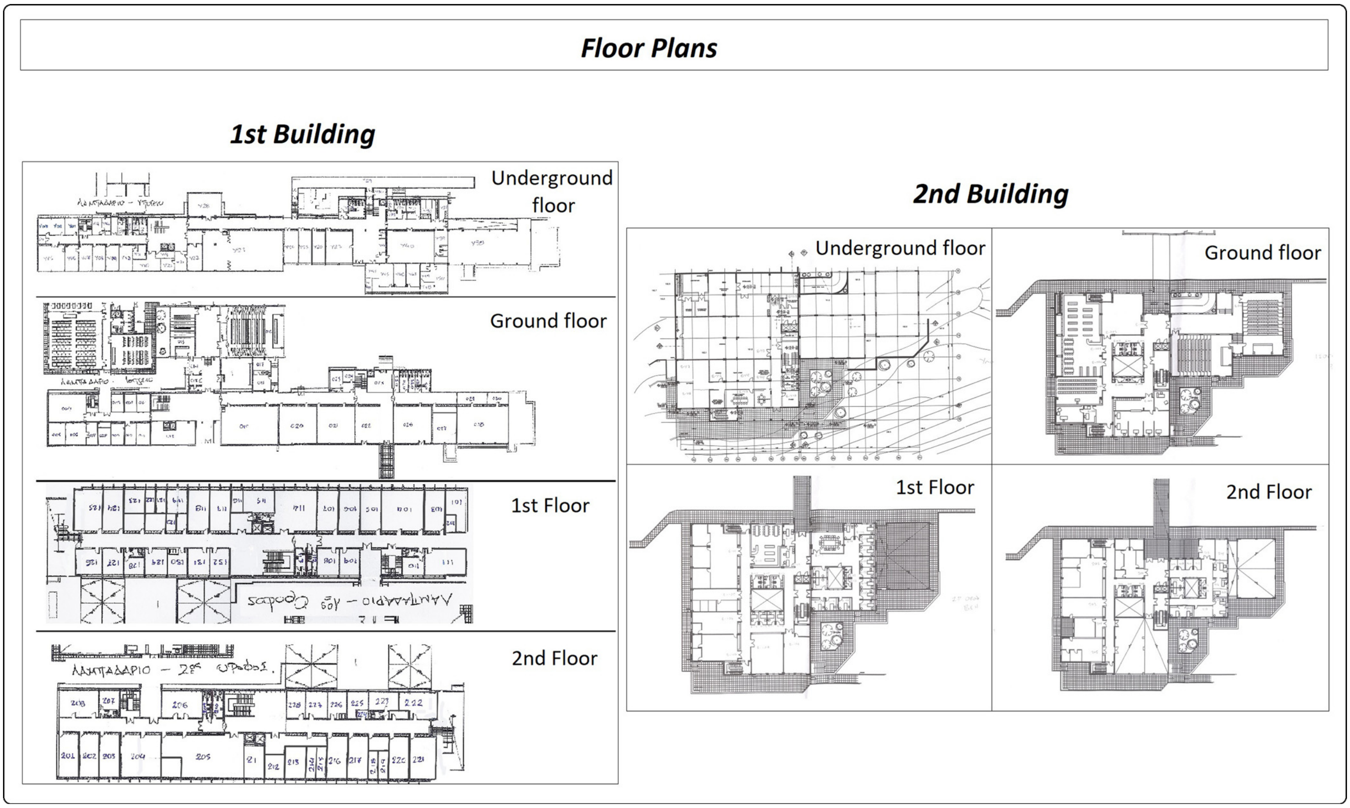

Fig. 12. Floor plans of the underground floor, the ground floor, first floor and second floor of the 1 st (left) and the 2nd (right) building, at the scale of 1:200.

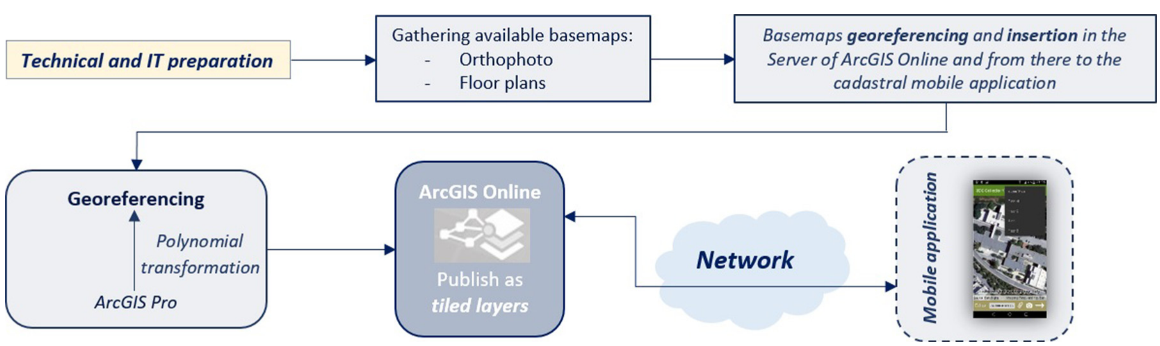

Fig. 13. Technical and IT data preparation procedure of the practical experiment.

achieved.

4.4. Results

Once the overall procedure is completed, the generated crowdsourced 3D property models may be vizualized through the 3D scene viewer provided from ArcGIS Online. Simultaneously, the corresponding cadastral information concerning each of the declared properties may be viewed either by selecting the 3D building unit model or by accessing the database and navigate through the relationships between the DBMSs' classes (Fig. 17). For the evaluation of the results regarding the achieved accuracy, quality and completeness, a comparison with the reference data was conducted. As reference data, the architectural plans of each building's floor were utilized. Based on Gkeli et al. (2018), the comparison was conducted between the reference data and the digitized unit polygons referenced to each one of the building floors. The results were satisfactory as there were no significant discrepancies between the compared data as the average accuracy deviation between the compared datasets was 0.21 m and their maximum and minimum deviation was approximately 0.75 m and 0.03 m, respectively (Fig. 18). Furthermore, the generated 3D models were correctly positioned in 3D space while the small shape defects are caused by the imported errors in the digitization process.

5. Assessment of the proposed technical solution

The establishment of a functional 3D cadastre aims to support the government administration to provide an effective and transparent system capable of securing property rights, facilitate property valuation, managing real estate markets in modern cities, as well as other necessary urban reforms. Due to the difficulty of the traditional cadastral field surveys, the complexity of work influences the time of their completion leading to delays and the gradual increase of the cadastral procedure's costs. Thus, a fast, cost effective and reliable solution is needed. As it has been proven at earlier stages of this research, crowdsourcing techniques may be utilized for the implementation of 2D (Mourafetis et al., 2015; Apostolopoulos et al., 2018; Gkeli et al., 2016) and also 3D cadastral surveys (Gkeli et al., 2017a,b,c,d; Gkeli et al.,

Fig. 14. Group of volunteers in cooperation with the team leader, during the registation of a meeting room of the School of Rural and Surveying Engineers of the NTUA.

2018, 2019) providing promising results in terms of cost, time, geometric accuracy and reliability. Although 2D crowdsourced cadastral surveys have been tested and their pilot implementation is already started in some cadastral agencies (Cetl et al., 2019) the 3D crowdsourced cadastral surveys still need investigation. The proposed crowdsourced technical solution combines the current initiatives of the scientific community and produces a modern innovative approach for the initial implementation of 3D cadastral surveys, by setting the basis for the implementation of a Fit-For-Purpose 3D cadastre.

Cadastral surveys constitute the costliest and most time consuming phase of cadastral systems' implementation. In Colombia, where the 60 % of the rural land parcels need to be formalized, an amount of about US $ 1.6 billion and long time (much more of seven years) is required in order to achieve this goal (Molendijk et al., 2018). In Greece, severe delays in cadastral surveys have emerged in more than 340 areas, due to errors and discrepancies of the formal cadastral surveys in the properties' location and boundaries. Multiple formal re-surveys of the problematic areas have been attempted, without the involvement of the rights holders, as the specifications did not require their involvement in the field surveying, leading to general misplacement of land parcels.

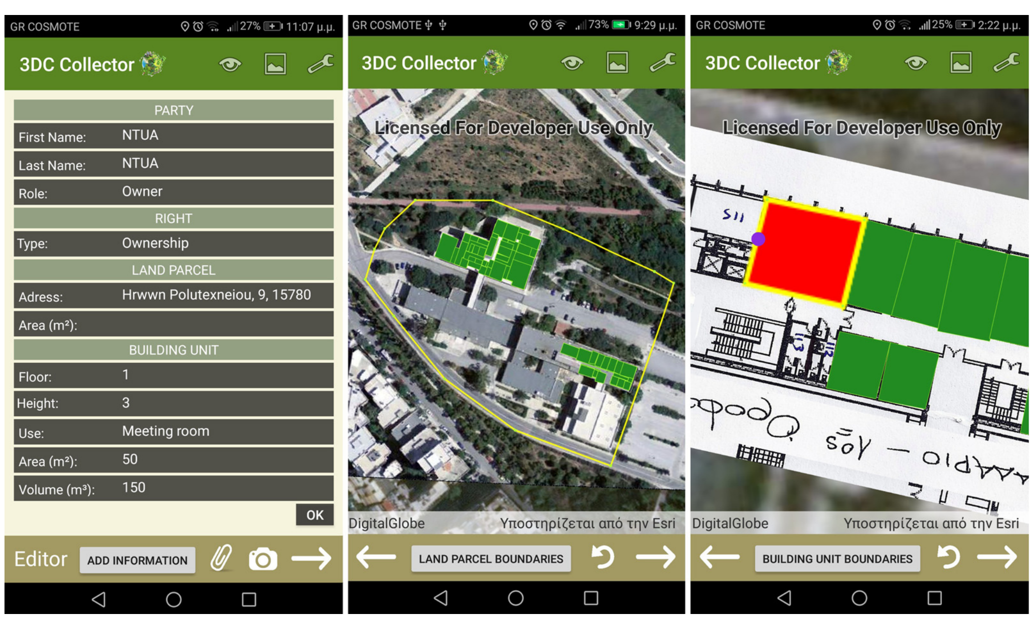

Fig. 15. Example of the recording process through the developed mobile application, including (left) the insertion of the adequate information, (middle) the polygon digitization describing the land parcel and (right) the the polygon digitization describing the building unit, on the basemap.

Fig. 16. 3D models of the declared properties above (left, middle) as well as above and below (right) the ground, using the 3D Model tool of the developed mobile application.

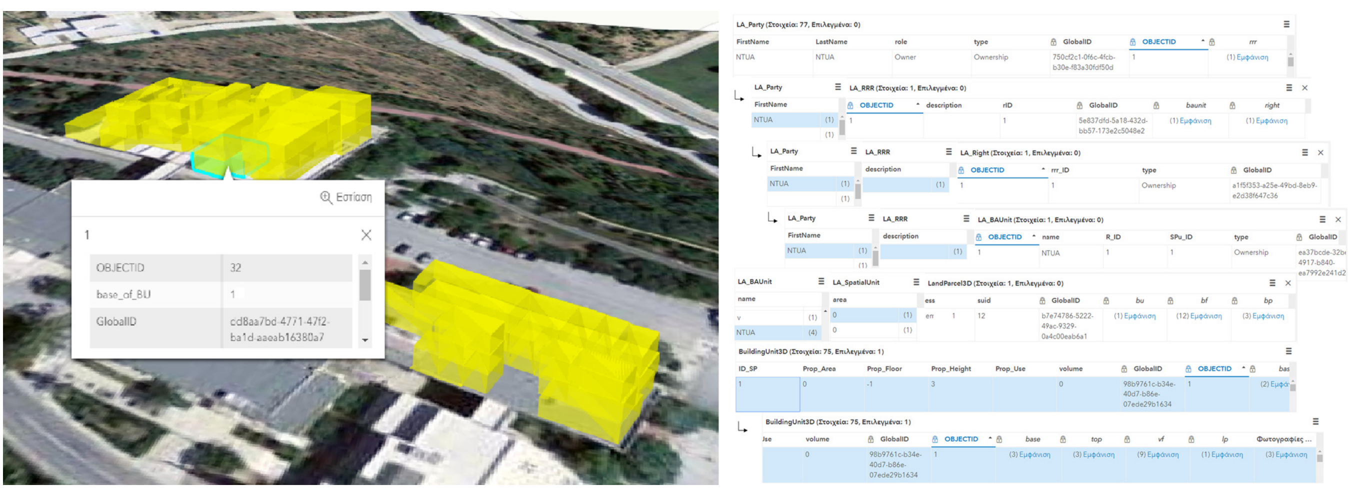

Fig. 17. Visualization of the generated crowdsourced 3D building unit model in ArcGIS Online. Inspection of crowdsourced cadastral information either by selecting the 3D building unit model (left), or by accessing the DBMS in ArcGIS Online (right).

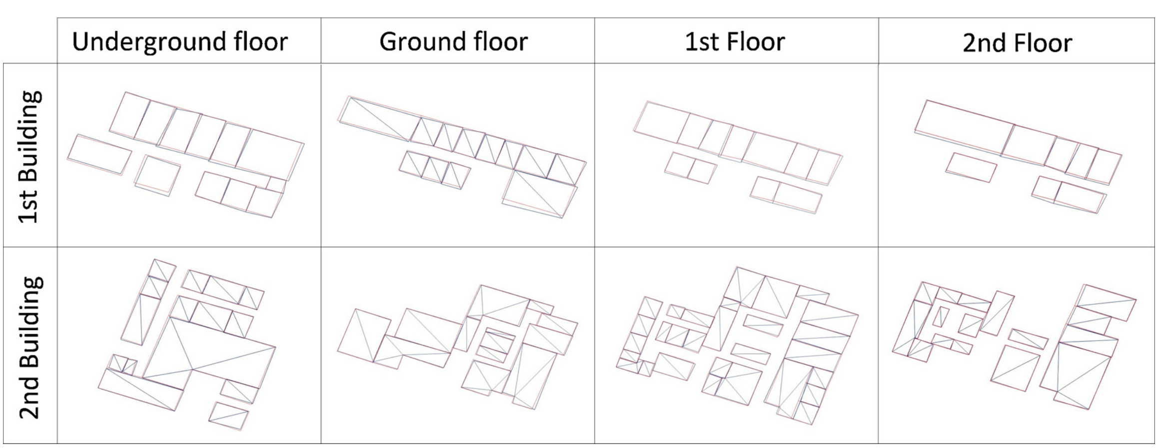

Fig. 18. Comparison between the digitized polygons (in blue) and the reference data (in red), for each one of the studied building floors (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

These practices led to confusion, delaying the real estate market functioning for decades and increasing extremely the cost of the whole property registration process. The rights holders were forced to pay extra fee, more than 2000€, to private lawyers and surveyors in order to submit an objection for correction (Basiouka and Potsiou, 2012a). Although these incidents represent only a part of the current international cadastral situation, they outline some of the major problems regarding the finances and duration of the cadastral surveys. The uncertainty of ownership rights till the completion of the property registration, blocks the real estate market and rights holders, in a stagnant state. Introducing citizens participation, low-cost modern IT tools and crowdsourcing techniques in the formal cadastral procedures showed that the participation of right holders, who know better the boundaries and location of their properties, in this process can minimize the time and costs of the cadastral surveys and more important it can eliminate the errors (Basiouka and Potsiou, 2012a,b; Mourafetis et al., 2015; Apostolopoulos et al., 2018; Molendijk et al., 2018; Gkeli et al., 2016; Rahmatizadeh et al., 2016).

Through the crowdsourced approach presented in this research, the registration of each property lasts about $10-12$ min (in average), which is hard to achieve with traditional surveying procedures. Thus, the reliability of the cadastral surveys is increased, as the responsibility for the initial data collection process is transferred to the rights holders. According to previous researches (Basiouka and Potsiou, 2012a), citizens are willing to participate in a crowdsourced procedure in order the time, costs and errors of cadastral surveys to be reduced, and therefore the real estate market can start operating again. Nevertheless, the motivation and activation of rights holders through methods such as gamification (Apostolopoulos et al., 2018), may strengthen the reliability of the process.

The prototype mobile application, developed by the authors, utilizes the current algorithms and techniques in 3D reconstruction (Gkeli et al., 2017a), and thus parametric 3D modelling (Model-driven approach) can be successfully implemented automatically, despite the known difficulties in 3D modeling techniques that make it an even more time consuming and tedious process than the one for a 2D Cadastre. Rights holders / Users do not need to have a certain level of 3D modelling skills in order to contribute to the registration procedure. The interface of the mobile application is appropriately configured in order to lead and simplify the registration procedure, minimizing the inserted errors and therefore increasing the reliability of the collected cadastral data. According to the results of the case studies, users do not face any particular difficulties understanding and using the developed application. The registration process is fast enough and it was completed successfully without major problems. Nonetheless, in such crowdsourced projects there is a trade-off between time and achieved accuracy. As it proved by the practical experiment, the recording procedure is fast with an accuracy of $RMSExy = 0.21$ m. The results of implementation are satisfactory as they meet the current accuracy specifications of the Greek Cadastre which for urban areas is 0.56 m (RMSExy). The produced 3D models are correctly positioned in the 3D space. Each 3D model is accompanied by the corresponding descriptive information, thus facilitating the post-processing and querying procedures, useful in various applications. The approach presented here is a fit-for-purpose approach, able to safeguard citizens' rights, with accuracy that may be improved gradually.

The adoption of LADM standard in the proposed procedure, establishes a standardization in cadastral data management and facilitates the communication between the involved parties within one country or between different countries ensuring transparency, cross-border trade, and in general data exchanging in heterogeneous and distributed land administration environments. By making the necessary adjustments in the proposed framework, it may be adopted by various countries utilizing the available spatial data infrastructure in order to proceed with 3D recording. The proposed technical solution is evaluated on the basis of ideal conditions, assuming that the necessary spatial data infrastructure/plans are available, which maybe the case for the majority of relatively new constructions in the developed countries. So far this research is at an initial stage and it presents a proposal for the implementation of 3D cadastral surveys in the near future. As a next step of this research, a more in-depth investigation regarding the absence of accurate registration basemaps for the land parcel and for the various building levels digitization will be carried out. As first thoughts, in the absence of professional floor plans or/and orthophotos of high accuracy, an orthophoto of less accuracy, or even an aerial image, may be used, reducing the geometric accuracy of the 2D cadastral information significantly. In the latter case, the rights holders may also be asked also to compose the necessary buildings' floor plans for the identification of the individual property units on each building level.

Despite the fact that in the current practical experiment, the selected volunteers had digital skills, it is noted that the results of a crowdsourced procedure may be greatly improved after a proper training and briefing of the rights holders/ users by a trained team leader or a professional surveyor (Apostolopoulos et al., 2018; Gkeli et al., 2016). The presented case study constitutes only a practical example in exploration of the function and results of the proposed framework. A pilot implementation of the proposed framework is intended at a later stage of this research. As the next step of this research, the proposed technical system and methodology is intended to be tested under real circumstances with citizens with average digital skills in order to obtain results capable to optimize both the technical and methodological crowdsourced frameworks.

6. Conclusions

The rapid economic, digital and social transformation through the last several years, has led to multiple rearrangements regarding the land administration procedures. 2D cadastre is inadequate to give clear information about the legal status of real estate in cases of multiple use of space with overlapping and complex property issues, the implementation of a 3D cadastre is essential. 3D crowdsourced cadastral surveying is an innovative field, with huge potential. Combining 3D crowdsourcing procedures with LADM standards new perspectives emerge for the initial implementation of 3D cadastre. The proposed framework constitutes a first step towards this objective. According to the test implementation and its assessment, the proposed framework can produce an accurate and reliable 3D information model depending on the accuracy of the available basemaps, and the internet provision, while the developed application is easy-to-use. As a next step of this research, a more in-depth investigation regarding the absence of accurate registration basemaps for the land parcel and for the various building levels digitization, as well as a larger scale pilot implementation, will be carried out. Through proper and brief training of the rights holders, the reliability of the proposed procedure will be increased. Thus, this approach may constitute the basis of an initial implementation of a FFP 3D cadastre.

CRediT authorship contribution statement

Maria Gkeli: Software, Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Chryssy Potsiou:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision. **Charalabos Ioannidis:** Conceptualization, Supervision.

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