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3D crowdsourced parametric cadastral mapping: Pathways integrating BIM/IFC, crowdsourced data and LADM

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ABSTRACT

This paper is part of a doctoral dissertation (PhD) research aligned with global trends aiming to develop practical technical tools for the collection, management and visualization of three-dimensional (3D) property rights in urban areas. Recently, the Building Information Models (BIMs) claim a prominent position in the field of 3D cadastres and the digital twins of the cities. In addition to all other building information, the BIM can also provide data about the exact boundaries of all kind of legal spaces (e.g., property ownership rights as well as land use restrictions), under the support of Industry Foundation Classes (IFCs). However, the utilization of BIMs for 3D cadastral surveys is still accompanied with two main drawbacks. The first refers to BIMs limited availability, as till now they mainly encounter in new large constructions. The second refers to the complexity in defining the exact geometric location of the legal boundaries regarding the exterior/interior partitions of the construction and of the common spaces. The latter parameter is formed on the basis of the current legal legislation in each country. Through in-depth investigation of the current legal framework of each country it may be possible to visualize the various 3D legal spaces within complex constructions and thus to facilitate the integration of existing BIMs in the development of 3D cadasters that will enable a better understanding and communication of all involved parties in the operation of cross-boundary real estate markets. In parallel, crowdsourcing has already been proved to be a powerful data collection method for the initial participatory implementation of fast, reliable and affordable 3D cadastral surveys, utilizing all capabilities provided by the latest low-cost devices, mobile services (m-services), open-source software (OSS) and the international standard of Land Administration Domain Model (LADM ISO 19152). If no precise 3D building models are already available, the currently available 2D architectural plans combined with the additional geometric and descriptive cadastral information may be utilized for a participatory crowdsourced cadastral survey of the 3D property units. In this paper a 'two-route' crowdsourced approach is described. This approach suggests both the use of existing BIMs – those available – to proceed with 3D crowdsourced cadastral surveys of those constructions, as well as the use of 2D georeferenced basemaps (e.g., orthophotos for the compilation of 2D crowdsourced cadastral surveys, and all existing architectural floor plans of the constructions) to proceed with 3D crowdsourced cadastral surveys of all other constructions. A database schema describing the linkage between LADM standard, BIM/IFC and 3D crowdsourced geometric and descriptive cadastral information is developed and presented. A hybrid mobile application enabling the manipulation of BIM/IFC descriptive data – if existing; the collection of 3D crowdsourced geometric and descriptive information by property owners/users/non-professionals; the registration of the cadastral data and their relationships within a LADM-based cadastral geodatabase; the automated generation of 3D property unit models as block models (LoD1), using Model-driven approach; and the objects visualization in real-time, are developed. An investigation regarding the legally correct representation of the location of property unit boundaries, focusing mainly in the Greek territory is conducted. A practical experiment for each one of the cases of the 'two-route' crowdsourced approach is implemented, for two multi-storey buildings in the city of Athens, Greece. The potentials of the proposed crowdsourced solution as well as the achieved geometric accuracy – in the absence of BIM – are discussed and assessed. The results show that integrating BIM data with cadastral information derived from crowdsourcing, may significantly contribute to the implementation of 3D Cadastres, providing also a better visual understanding of 3D property rights. Nonetheless, even in the absence of a BIM the achieved accuracy seems

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to satisfy the cadastral specifications of the Greek cadaster enhancing the potential of exploiting crowdsourced data in the initial phases of the cadastral formal procedures.

1. Introduction

Rapid urbanization is growing with the scientific predictions to estimate that by 2050 the two-thirds of the population will be living in cities (United Nations, 2018). This exerts great pressure on the existing urban structures and land uses, forcing the 3D spaces in cities to be optimized into multiple individual property units, with legal and physical subdivisions in both vertical and horizontal dimensions. A 3D cadastral system is needed in order to provide Accurate, Assured and Authoritative (AAA) information about the multi-dimensional property Rights, Restrictions and Responsibilities (RRR).

Several attempts for the creation of 3D Cadastres have been initiated worldwide, including a wide variety of potential solutions and important findings, regarding the subdomains such as the data type, data modelling, system architecture and visualization (Vandysheva et al., 2011; Stoter et al., 2012; Stoter et al., 2016). With the emergence of the international standard of Land Administration Domain Model (LADM ISO 19152) in 2012 the researchers' interest is focused on linking the legal and physical counterparts of the 3D cadastral objects, through the utilization of several technologies, application schemas and technical models such as CityGML, IndoorGML, BIM/IFC, LandXML, InfraGML, etc. (Thompson et al., 2016; Atazadeh et al., 2018; Alattas et al., 2018; Gkeli et al., 2018; Kitsakis et al., 2019). BIM has attracted maximum attention as it is widely used and it contains rich geospatial content regarding the structure of the buildings. The spatial extend of the 3D RRRs of the properties included in a BIM may be accurately defined through the Industry Foundation Classes (IFC) data model, based on the current legislation of each country (Oldfield et al., 2017; Barzegar et al., 2021). However, the commencement of such a cadastral approach based exclusively on the existing as well as on the generation of new BIMs requires considerable costs and time, preventing the fast completion of a 3D property registration system, thus intensifying the current challenge and delaying the well-functioning of modern property markets. In parallel, recent research has shown that the development of a reliable, qualitative and affordable solution for the initial implementation of a 3D cadastre may be feasible by utilizing the currently available geospatial infrastructure of a country in combination with modern Information and Communication Technology (ICT) tools, low-cost equipment, crowdsourcing techniques, web services, mobile services and open-source software; (Vučić et al., 2015; Ellul et al., 2016; Gkeli et al., 2018; Potsiou et al., 2020a; Gkeli et al., 2020a; b; Gkeli et al., 2021a; Gkeli and Potsiou, 2021b). A hybrid approach exploiting the potential of the existing 2D (orthophotos, architectural floor plans, aerial photos, OSM etc.) and/or 3D data sources (such as BIMs) may significantly reduce the costs and speed up the processes for the implementation of 3D Cadastres (Oldfield et al., 2017).

The main objective of the research presented in this paper is to provide a practical technical tool and a crowdsourced methodology for the initial implementation of 3D cadastral surveys in a fast, cost- effective and reliable way, applicable in many countries.

Greece is an EU country that has not yet completed the 2D Cadastre for all of its territory. The compilation of a functional cadastral system, able to manage both the 2D and 3D aspect of the cadastral objects is considered to be an urgent issue to safeguard land tenure and ensure access to credit, to assist the economic recovery of Greeks and to support good governance. In this paper a 'two-route' crowdsourced approach is proposed, aiming to assist the completion of 2D Cadastre in areas where it is not yet implemented, as well as to support the compilation of 3D cadastral surveys utilizing the currently available 2D and 3D geospatial data sources, and exploiting the potentials of modern technological achievements.

Section 2 presents basic information regarding the structure of the Greek Land Registry and the current Greek legislation, investigates the law regarding the private property boundaries on the various structural elements of a building and aims to draw important conclusions for the determination of the spatial extent the private rights and their legal boundaries.

Section 3 presents the most common cases of defining the location of property boundaries, based on the recent literature.

Section 4 presents the proposed framework describing its technical and methodological parts. Section 5 presents a practical experiment of the developed system in two multi-story buildings in the city of Athens, Greece, as well as the results of the overall procedure.

Finally, Section 6 presents the main conclusions referring to the perspectives, the geometric accuracy, the cost, duration and reliability of the proposed crowdsourced solution as a basis for the compilation of a 3D Cadastre in Greece, as well as some thoughts about our future research in this field. It is noted, that the identification of the various types of the legal objects is outside of the scope of this study. Our main interest is to approach this endeavor from a technical point of view.

2. The 3D legal definition of real property in Greece

The Hellenic Cadastre (HC) project started in 1995 with the Law 2308/1995 (Government Gazette A΄, 114/15–06–1995) (Hellenic Cadastre, 2022; Potsiou et al., 2001). HC is a unified, public, systematic and constantly updated title registration information system, which contains spatial and attribute records of each land parcel, in digital form. In contrast with older operating systems, HC is a 'parcel-centric' digital Geographic Information System (GIS) that is aimed to cover the whole Greek jurisdiction. Based on the 24th Article of the Constitution of the State, the obligation for the compilation of the National Cadastre is assigned to the state.

The HC procedure of cadastral surveys starts with the declaration of an area under cadastral survey and is completed with the issuance of completion's declaratory act of the cadastral survey (Gkeli et al., 2016). The cadastral surveys are conducted by private cadastral companies (contractors) which are selected by the Hellenic Cadaster Agency (National Cadastral Mapping Agency - NCMA). Prior to the field processes a draft cadastral basemap is constructed, utilizing a recent orthophoto and any existing spatial information from other relevant projects (urbanization projects, city plans, land consolidation projects, projects for the determination of the coastal line etc.). Next, the submission of declarations regarding the property rights is conducted by the right holders, either online or at the temporary cadastral offices. Right holders are asked to submit personal information as well as descriptive and geometric information about the properties and the property rights, along with any existing legal document proving their rights. Additional data, enabling the better localization and identification of the declared property on the draft cadastral map, are also provided by the right holders. A pre-existing field survey, a digital orthophoto (provided by the NCMA) depicting the property boundaries marked by the right holder, or coordinates of a central point of the land parcel, derived by a hand-held GPS, are some of the options available (Mourafetis and Potsiou, 2020).

In the next phase, the declarations are gathered, processed and merged with other collected data provided by the public authorities. In cases where discrepancies in the collected data are detected, the contractors must proceed with field cadastral surveys to correct these data. Also, if needed, additional data may be supplied by the right holders. Once the processing phase is completed, the right holders are informed about the outcome and are asked to submit objections-if needed, which are examined by an independent administrative committee. Once the examination procedure is completed, the final cadastral tables and maps are created. These records are called Initial Registrations as they constitute the first registration in the HC. Finally, the temporary cadastral office is closed and the existing Land Registry Office in the area is replaced by a permanent Cadastral Office (Gkeli et al., 2016).

The legal framework, on which the HC is based, is consisted of the Civil Law, the Greek Civil Code, the Legislation that has been adopted specifically for the HC and the Customary Law. Each has a different role in defining the legal boundaries of the RRR as well as in establishing the registration method used. In 1946, the Civil Code regulated issues related to the right of ownership over land, following the Roman law, according to which "superficies solo cedit", meaning that the owner of the land is both the owner of whatever lies above or beneath the surface. This concept of ownership was introduced in the Hellenic legislation by the Byzantine-Roman Law (Decree 23.02.1835) and recognized by the Civil Code of 1946 (articles 948, 953, 955, 1001, 1057, 1058, 1282) (Papaefthymiou et al., 2004). Furthermore, condominiums or horizontal properties recognized with the article 1 of the Law 3741/1929 and the Decree-Law 1024/1971, introducing the two main types of horizontal properties that are encounter in Greece. The first one refers to separate horizontal properties on a specific condominium unit (per floor or floor section), while the second one refers to horizontal properties with co-ownership proportionally on the communal parts of the property. With the article 1002 of the Civil Code, the horizontal properties are defined, limiting the vertical extend of properties RRR, which according to the article 1001 of the Civil Code these vertical limits are extended both above the surface and below the ground, unless another law applies.

The introduction of the Civil Code ceases the appliance of the Customary Law in the Greek territory. However, besides the abovementioned property rights, other more complex customary property rights, pre-existing the establishment of the Civil Code, are still in force. These real property rights are related to 3D space and constitute special property rights, located over, under or both over and under the ground surface, with or without ownership right on the land parcel. Two of the most known customary property rights are: (i) "Anogeio", consisting a property object lying over the land parcel with no share on surface parcel ownership, and (ii) "Katogeio" consisting a property object including only the ownership of the land parcel, with the rest of the structures on land consist the "anogeio" objects. Of course, in Greece there are several other types of such special real property right encountered. In the context of the HC, these types of customary properties are defined as Special Real Property Objects (SRPO) (Dimopoulou et al., 2006; Dimopoulou, 2015; Kitsakis, 2019).

Nevertheless, despite the legal or customary definition of the 3D extend of these real property rights, their identification in the HC remains in 2D. A horizontal property, usually compiled by a notarial deed, is entered in the cadastral database with the form of descriptive information (e.g. building number, shared property number, floor, area, use, year of permit, coordinates). The 2D building outlines are not shown on the cadastral maps; only the 2D land parcel, the building number and the linear boundaries of the vertical properties. Furthermore, the SPROs are presented either as point features into the land parcel or with their polygonal boundaries at a different level from the land parcels, according to their type. It is noted, that apart from the abovementioned property rights, there is a variety of other proprietary objects that require both the 2D but foremost their 3D localization, but their registration is not provided by the specifications of the HC. Such objects are the subway, the utility cables and pipes, the telecommunication cables, the underground tunnels, etc. Either way, the declared property rights remain in 2D despite their 3D spatial extend, complicating the understanding of the individual rights limits and enhancing the emergence of disagreements and disputes.

Cadastral procedures do not distinguish between stratified or non-stratified real property units. In the Civil Law jurisdictions, no 3D real property legislation is established, thus only the submission of the necessary documentation defined by the law is required. The most important requirement, is the clear representation of the real property boundaries on the cadastral maps, according to the Greek Law 2664/98, Art. 11. (4). However, the current legislation does not explicitly provide for 3D real property formation. This is amplified from the fact that the legal provisions are based on technical systems with 2D drawing and recording capabilities (Kitsakis, 2019).

Law 4412/2016 (Government Gazette A΄, 147/08–08–2016) harmonizes with the provisions of the Directives 2014/24/eu and 2014/25/eu. According to that law the EU Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar. However, neither these provisions have been implemented, nor instructions and templates have been issued on how these provisions can be applied (declaration, specifications, deliverables, method of payment, etc.). In 2019, this matter comes again to the fore by the Law 4723/2019 (Government Gazette A΄, 134/9–8–2019), which updates and replaces the National Digital Strategy by the Digital Transformation Book. The Digital Transformation Book is published by a decision of the Minister of Digital Government and includes the basic principles, framework and guidelines for the digital transformation of the Public Administration, but also of the private sector, defining the specific principles governing each initiative. Thus, by Decision 40072/1492 of the Greek Ministry of Environment and Energy - General Secretariat for Spatial Planning and Urban Environment in 2021, a Support Group consisted by experts aiming to promote the European BIM, was established. This step is very important paving the way for the future implementation of a 3D Cadastre in Greece.

3. Property boundaries location

In addition to the descriptive determination of the property boundaries, their location may be better defined, especially in the case of condominiums, so that the separation of the individual properties and the common spaces, can be visualized. By seeing the boundaries of the properties, the 3D extent of the legal RRR may be better defined. This separation could be implemented using as reference the structural elements of a building, namely the floors, the walls and the ceilings. However, the legislation of each country differs in this regard, while usually such definition is vague. Nevertheless, some commonly encountered approaches exist worldwide, based on the respective national laws of the countries.

The first approach considers as boundaries the conceivable lines passing through the middle of the floors, walls and ceilings. Thus, the boundary between individual private properties or an individual property and the common space, is located in the middle of the horizontal (e.g. floors and ceilings) or vertical (e.g. walls, windows, doors) structural elements of the building, ignoring any additional existing elevated floors or suspended ceilings (Fig. 1 - left). The second approach considers as boundaries the conceivable lines tangent to the interior or exterior face of floors, walls and ceilings. Thus, as property boundaries the interior faces of the floors, lying on the top of the elevated floors (if existed); the interior surface of ceilings, upon the underside of suspended ceilings (if existed), and the interior faces of walls, including any additional coverings; are considered (Fig. 1 - middle). Similarly, the exterior boundaries are defined following this rationale (Fig. 1 - right).

In addition to these approaches, there are others that place the boundaries in a different location based on national Ownership Laws, Civil laws, Common Laws or even Customary Laws. In the United States (Uniform Common Interest Ownership Act, 2014; Uniform Condominium Act, 1980), as property boundary, the surface of the unfinished floors, walls or ceilings is considered. In Sweden, the property boundaries are appropriately defined in order to serve all the potential practical use of the property (Kitsakis, 2019). However, besides the exploitation of the floors, walls, or ceilings as reference for boundaries determination, the definition of property boundaries may be

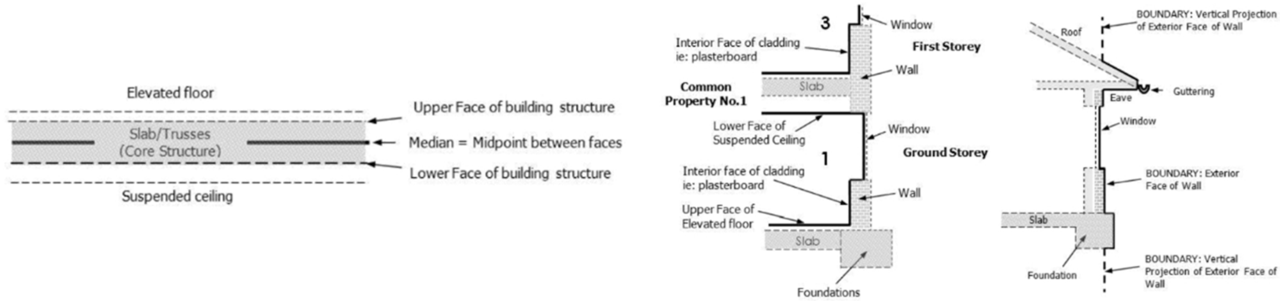

Fig. 1. Horizontal elements (floor and ceiling) median property boundaries (right). Vertical elements property boundaries - Interior surface (middle) and Exterior surface (right) (Government of Victoria, 2011; Kitsakis, 2019).

implemented regardless such structural elements. This approach is mainly followed by several European countries. By example, in Germany the parking spaces may be defined by permanent markings, as referred in the German Act on the Ownership of Apartments and the Right of Permanent Residency (Wohnungseigentumsgesetz, WEG) [Section 3 (2)]. Furthermore, the definition regarding the common spaces in condominiums can be conducted either by explicit reference of each common property's object or exclusively. In the last case, the common spaces include everything that is not individually owned (Kitsakis, 2019). A detailed reference regarding the elements consisting the common property can be also traced on the Civil Law based jurisdictions such as Greece (Law 3741/1929, art. 2), Switzerland (Civil Code, art. 712b) etc. As for Greece which is the main focus of this study, besides the boundaries of condominiums or horizontal properties, the boundaries of vertical properties are defined by the Decree-Law 1024/1971, as described in Section 2. However, the detailed definition of the location of the properties boundaries is not precisely described in the current legislation, contacting their definition to the interpretation of the respective laws and the main principles of the Customary Law.

4. Proposed technical framework

The proposed technical framework is an enriched version of our previous research on 3D crowdsourced cadastral surveys (Gkeli et al., 2020a; b,c; Gkeli et al., 2021a; Gkeli and Potsiou, 2021b), aiming to speed up the process of 3D cadastral surveys, reducing the costs and increasing the reliability of the collected data. This attempt requires community engagement, as the right holders and users of the buildings are called to be responsible for the identification of property rights, right holders and responsibilities, either by digitizing property boundaries on an available basemap, or by locating and selecting the property units on an existing BIM.

Our main objective is to provide a modern approach and an alternative technical tool for the future identification, acquisition, management, registration and representation of 3D property rights, mainly in urban areas. The proposed technical framework is structured in such a way that it can be adapted to the available infrastructure of each country, as Greece, which is examined in this research. It should be highlighted that the Hellenic Cadaster Agency has already developed an in-house software that enables citizen participation for the 2D data collection process (Mourafetis and Potsiou, 2020). Following this venture, it seems that the development of an alternative 3D crowdsourcing tool, such the proposed one, may be succeeded in a similar cadastral project.

The developed framework is consisted of two complementary parts: the technical part and the procedural part. The first part includes all technological sub-systems to be developed. The procedural part defines the implementation process of the 3D crowdsourced surveys through the developed systems.

4.1. Technical system architecture

The architecture of the developed technical system is composed of two connected parts: the server-side and the client-side. These two parts are communicated through a network connection. The first refers to the web server and the Database Management System (DBMS) where the collected data are stored and maintained. The client-side refers to the data capturing tool, which in this case is preferred to be a mobile device. In order to follow the global directions for the development of 3D cadastral systems, a database schema based on LADM standard is generated. For client-side an open-sourced mobile application for Android devices, is developed, while the storage and management of the collected data is conducted through the server of ArcGIS Online (ESRI, 2022).

4.1.1. Conceptual model

The proposed DBMS conceptual schema was developed through Enterprise Architect (EA) UML modeling tool from Sparx Systems, which supports the Geography Markup Language (GML) application schemas and the modeling of ArcGIS geodatabases, utilizing Model Driven Generation (MDG) Technologies. EA allows the generation of geodatabase conceptual schemas empowering the development of GIS applications. The developed geodatabase is based on our previous work, presented in Gkeli et al. (2020b) following the LADM standard's specification.

The basic classes of LADM, namely LA_Party, LA_RRR, LA_BAUnit and LA_SpatialUnit are preserved (Fig. 2), while some new classes are generated in order to support two individual categories of 3D objects. The division between these two categories rely on the geometry type with which the 3D object is defined in a GIS, that is either through points, lines and polygons or solely through multipatches. Thus, the first category of 3D objects tends to support the geometry of the land parcel and the geometry of the (custom) building unit, when no BIM is available. In contrary, the second category concerns exclusively the geometry of the building unit, as specified in the BIM.

The development of the new classes of the first category, is based on the fact that a valid 3D cadastral object may be defined as a 3D volumetric object formed by polygonal faces, composed of vertices, edges and relationships between them (Ying et al., 2015). Thus, following this rationale, the new classes supporting the geometry of the 3D land parcel and the (custom) 3D building unit, are generated respectively.

Aiming to emphasize the basic spatial unit of the land parcel, a new class named LandParcel3D (abbr. LP3D) is created. LandParcel3D is consisted of three new classes which represent the geometry of: (i) the land parcel in 2D (LP3D_BaseParcel), (ii) the vertically extending boundary faces, which form the 3D extend of the land parcel (limitless or limited) (LP3D_BoundaryFaces), and (iii) the set of the 3D points from which the polygonal faces are made up (LP3D_Points) (Fig. 3).

Similarly, a new class named BuildingUnit3D is generated aiming to function as the receptacle of all potential geometries that can be managed by the DBMS (Fig. 4). BuildingUnit3D class is divided in two subcategories, depending on the BIM availability. The first subcategory

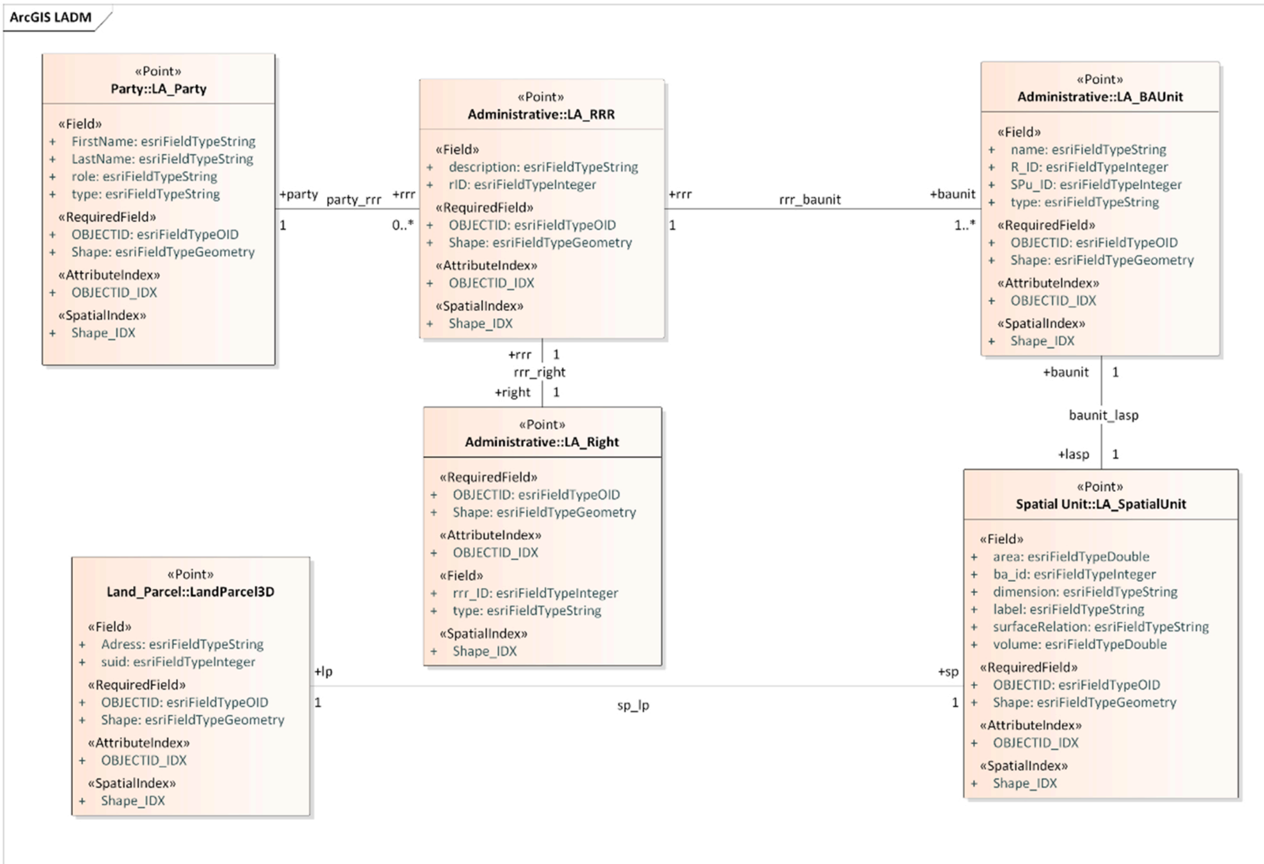

Fig. 2. Conceptual DBMS schema of the developed data model, based on the main classes of LADM: LA_Party, LA_RRR, LA_BAUnit and LA_SpatiaUnit.

includes the building entities which are customly created when no BIM is available (Custom_BuildingUnit3D) (Fig. 4). The Custom_-BuildingUnit3D class (abbr. CBU3D) is consisted of four new classes that represent the geometry of: (i) the building unit base polygon (CBU3D_Base), (ii) the building unit top polygon (CBU3D_Top), (iii) the vertically faces surrounding the building unit (CBU3D_BoundaryFaces), and (iv) the set of the 3D points from which the polygonal faces are formed (CBU3D_Points) (Fig. 5).

For the second subcategory of BuildingUnit3D, a new class entitled BIM_BuildingUnit3D is created (Fig. 4), aiming to include the multipatch geometry of the BIM's cadastral legal spaces. The development of this class is based on the capabilities of the Industry Foundation Class standard (IFC), which is one of the most widely used open BIM exchange models. With IfcSpace entity, the representation of volumetric cadastral spaces inside a building is feasible, and thus, the interior structural elements can be included into this entity, forming the required legal spaces of the cadastral objects, where the RRRs will be assigned.

BIM_BuildingUnit3D and Custom_BuildingUnit3D classes are linked with BuildingUnit3D class, with a XOR pre-condition, assuring the selection of one of the two categories per declaration, prohibiting their simultaneous utilization (Fig. 4). Each of these classes is also preserving the necessary information regarding the definition of the volumetric/multipatch geometry of a building unit (property) which are provided by the BuildingUnit3D class.

Finally, the developed database scheme is exported from EA as a Geodatabase Workspace XML Document (containing the ArcGIS schema) in order to be imported into ArcGIS Pro software. 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 solution.

4.1.2. The developed mobile application

An open-sourced prototype for Android mobile devices is developed to support the client-side of the proposed technical solution (Figs. 6–8). The developed application is based on the results of earlier stages of the current research (Gkeli et al., 2018; Gkeli et al., 2020a; b,c), including more functionalities for both the identification, collection, modelling and visualization of crowdsourced cadastral data, as well as for the manipulation and visualization of BIM/IFC data. The mobile application enables 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 property unit models as block models (LoD1), using Model-driven approach; the manipulation of BIM/IFC descriptive data; and the cadastral objects visualization in real-time.

The user interface is simple and appropriately configured in order to lead the registration procedure. It 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. However, the GPS is used only for a rough positioning in order to avoid gross errors during the orientation of the right holders in the 3D space. The mobile application gives the user the option to proceed either by utilizing the available cartographic basemaps (2D architectural plans, orthophotos, aerial photos etc.) or the BIM data, where available. Through selecting the desired option, the user may continue with the cadastral registration procedure.

For both registration options, the application allows the insertion of all necessary proprietary descriptive and geometric information for the declaration of the property rights; the capturing of property unit photos to verify the declaration; and, attaching other useful documents (e.g., plans, deeds etc.). Furthermore, the user should provide numeric information through the "Height" and "Floor" fields, defining the height

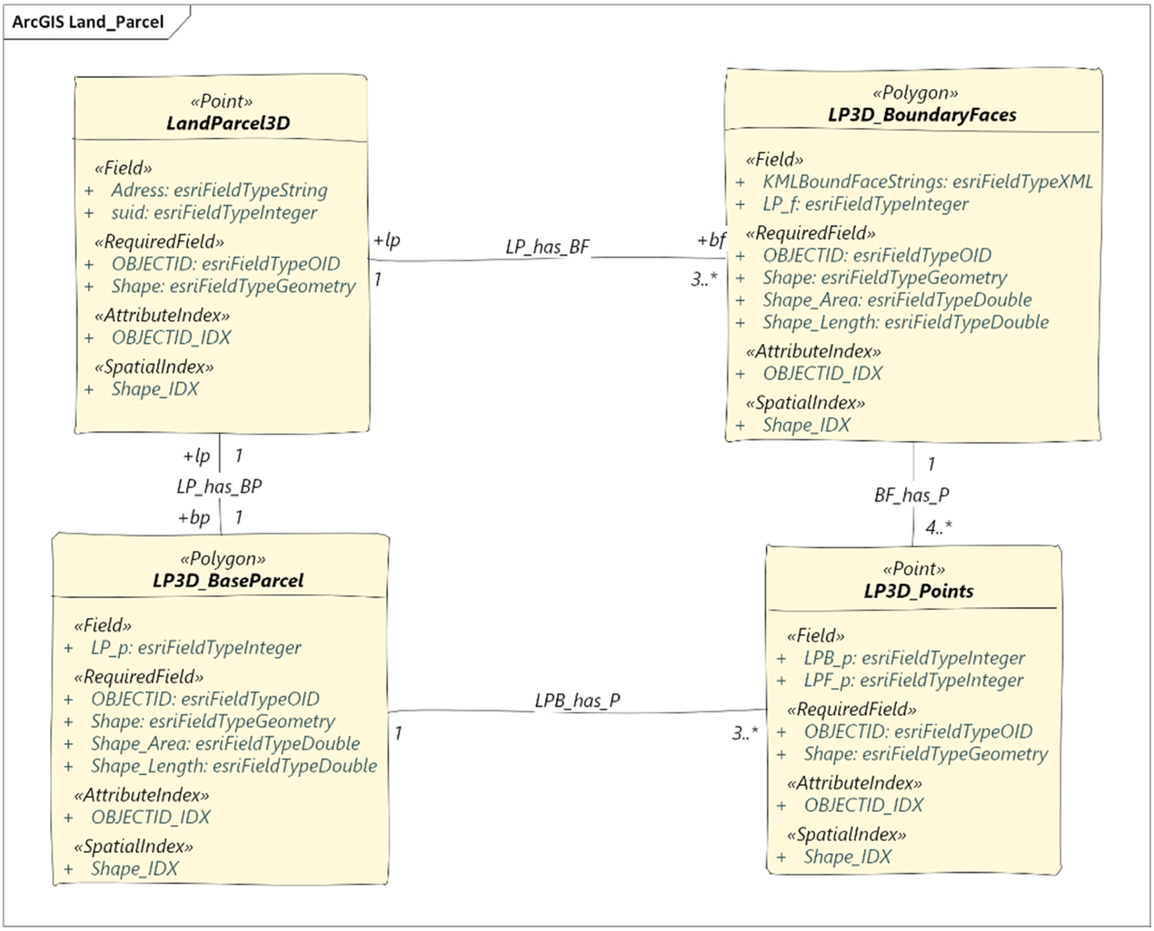

Fig. 3. Proposed conceptual schema defining the structure of a 3D land parcel.

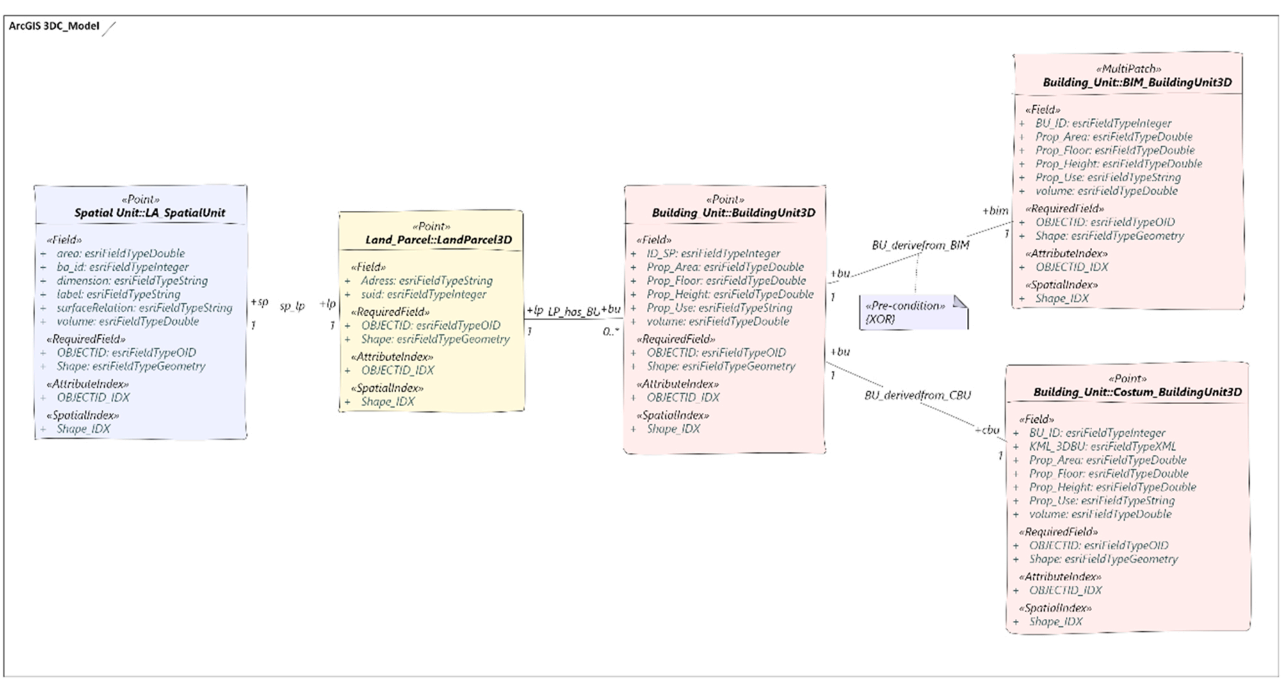

Fig. 4. Conceptual DBMS schema of the developed data model, describing the new classes of Land_Parcel, BuildingUnit3D, CustomBuilding3D and BIM_BuildingUnit3D; the relationships between them, as well as with the LA_SpatiaUnit class of LADM.

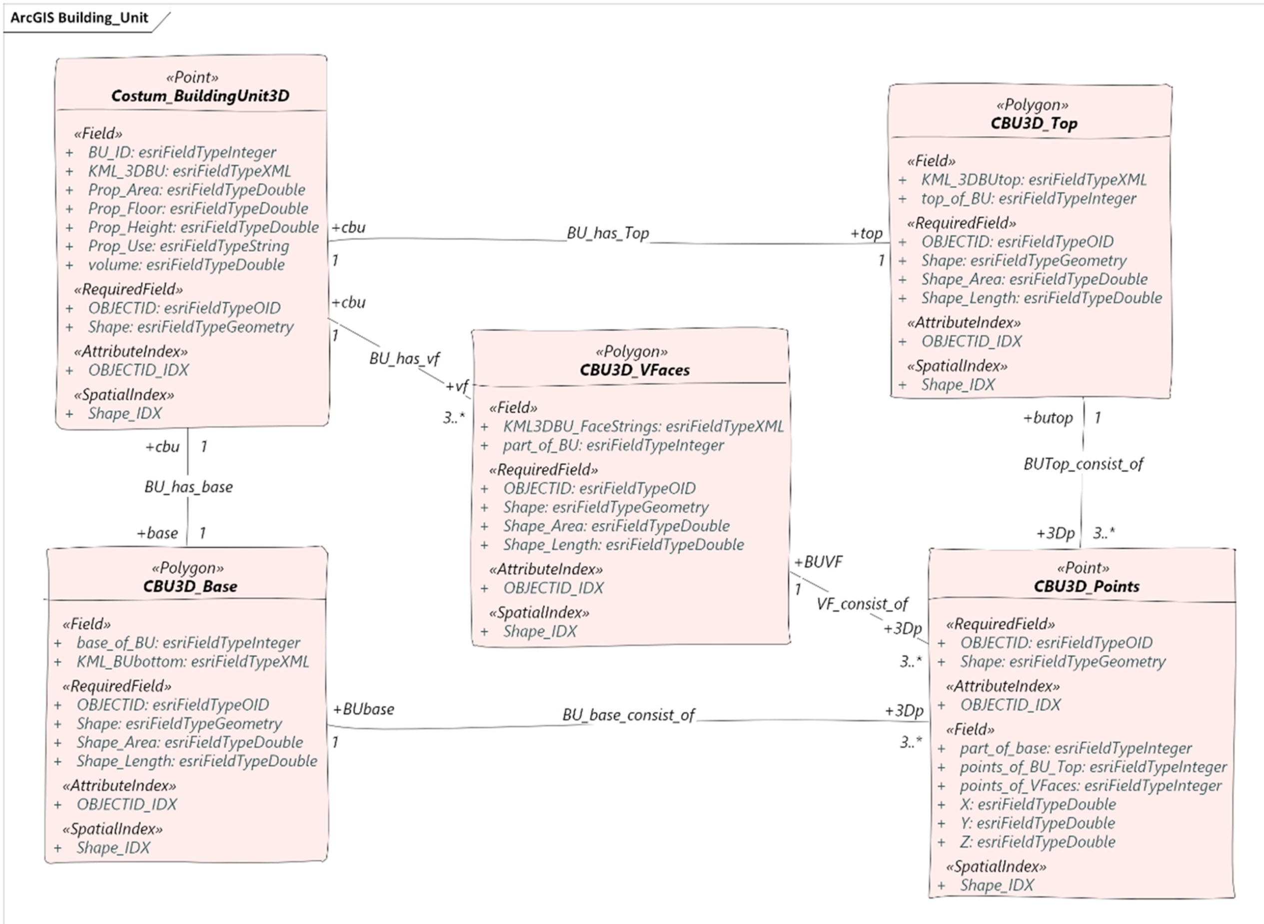

Fig. 5. Proposed conceptual schema defining the structure of a 3D polygonal building units.

and the number of the floor on which the declared property unit is located. These characteristics are of great importance, in order to proceed with automatic 3D modelling process (Figs. 7b,8c).

If the user proceeds with the "MANUAL SELECTION" option for cadastral registration, first the insertion of necessary descriptive information is conducted, and then the application provides a set of tools for the identification and digitization of the parcel boundaries and building footprint on the available basemap. In complex cases where the parcel or the building are not clearly recognized in the field (e.g., not spotted on the ground, but the legal boundaries not materialized in the field are described metrically in the deed), or they are not visible on the available basemap (e.g., due to vegetation, or the hidden parts on the orthophoto etc.), the mobile application provides a set of additional geometric tools facilitating their identification and digitization (Gkeli et al., 2020) (Fig. 7).

If BIM data describing the user's property unit in the building is available, the user may proceed with the "BIM SELECTION" option for cadastral registration (Fig. 8). The user may navigate throughout the 3D scene, locate his/hers property unit on the BIM and select it, by tapping it on screen. Next, the user may enter all the necessary cadastral information included in the information form, which the application requires to be completed. During the registration process, the user may enable or disable the physical (LoD3) or legal view (LoD1) of the property units presented in the available BIM, through the BIM view tool, provided by the mobile application (Fig. 6).

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, in the server of ArcGIS Online. It is noted, that beyond these 3D data capturing techniques, an innovative bluetooth sensor-based approach utilizing machine learning techniques, is also investigated during this research project. The first results were presented in Potsiou et al. (2020), however some further integration steps with the developed mobile application are needed, in order to proceed with a practical implementation.

5. Proposed crowdsourced methodology for hellenic cadastre

The proposed methodology aims to provide an alternative crowdsourced cadastral methodology for the initial implementation of 3D Cadastre in Greece, with the simultaneous collection of 2D cadastral data, in areas where the 2D HC is not yet implemented (Basiouka and Potsiou, 2012; Basiouka et al., 2015; Mourafetis et al., 2015; Basiouka and Potsiou, 2016; Potsiou et al., 2020b; Apostolopoulos and Potsiou, 2021). This proposal is based on our previous work presented in Gkeli et al. (2020a); b) and Gkeli, b) et al. (2021a), and adjusted to the current specification of HC. The main objective of the proposed procedure is to reduce time and costs and to simplify the most expensive and time consuming phase of cadastral registration process, which is the 3D cadastral data acquisition. By utilizing low-cost technology, (re-)using existing rich BIM data, and enhancing right holders' participation during this phase, the collection of the necessary geometric and semantic information concerning the ownership status and other rights, is accelerated with data reliability to be increased. The main idea of the proposed methodology is to continue and improve the current cadastral project in Greece in urban areas with a 3D cadastral survey and to proceed with the overall recording of the 3D crowdsourced cadastral information in a comprehensive LADM-based database. The overview of the proposed process is presented in Fig. 9.

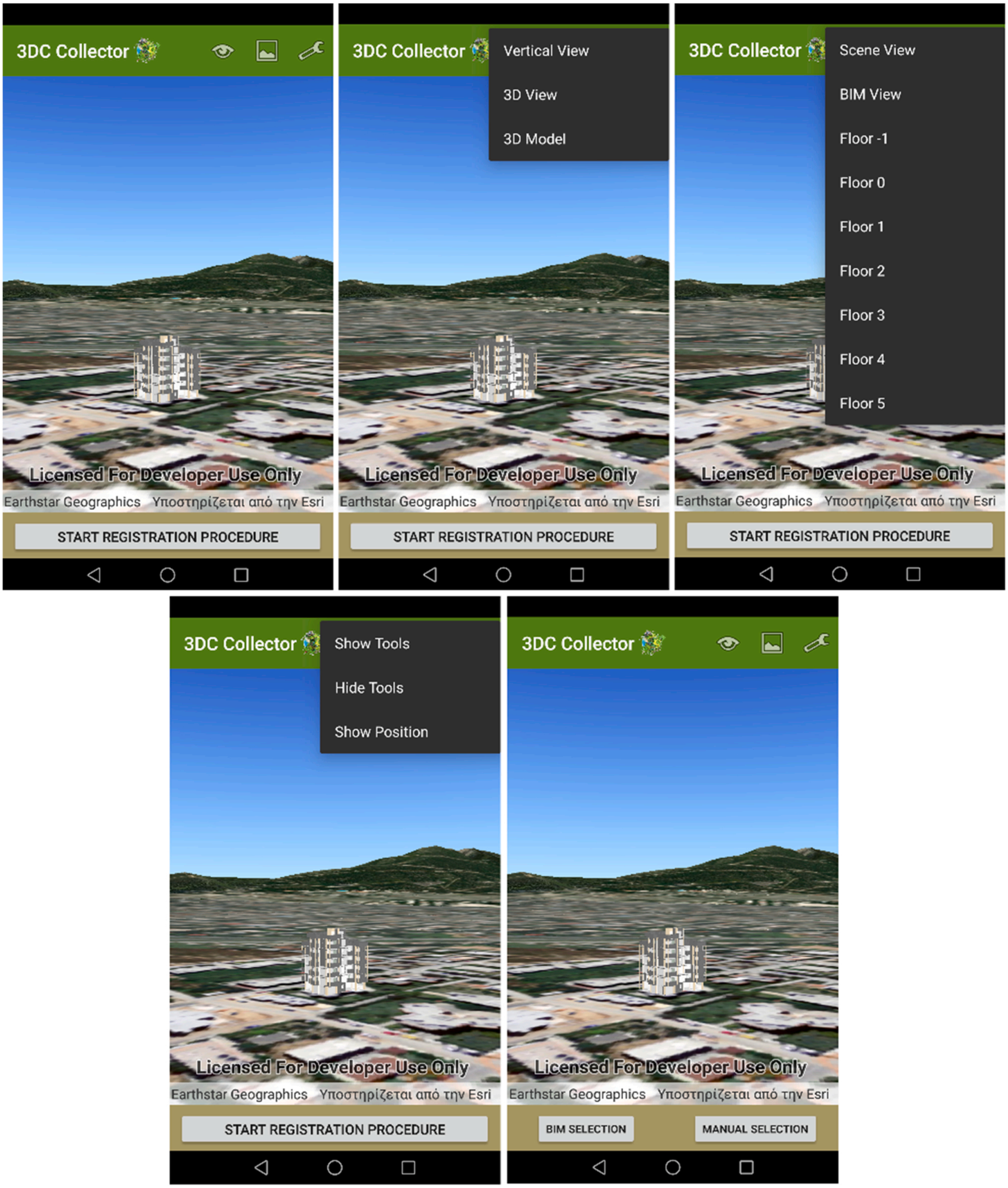

Fig. 6. Overview of the mobile cadastral application (top to bottom & left to right): (a) initial user's interface (b) tools for adjusting the viewing mode of the scene (c) basemap selection tools (d) representation of the additional geometric tools (Show tools & Hide tools) the coordinates of the GPS (Show Position tool) (e) tools for selecting the desired registration method (BIM SELECTION or MANUAL SELECTION).

The first phase of the proposed crowdsourced methodology starts with the compilation of a draft registration basemap, through collecting all the available cartographic/ geospatial, cadastral information and BIM data - if existing. In the next phase, the area under cadastral survey is divided to sub-regions and each one of them is assigned to a local team leader, who has an auxiliary and organizational role during the process. The team leader may be a professional surveyor or a trained volunteer, responsible to assist the overall data collection procedure and help the right holders with any question or difficulty concerning the process or the used software. In the third phase, team leaders are responsible to inform right holders about the benefits of the cadastral crowdsourced project and train them on how to use the cadastral mobile application. Besides that, NCMA should provide informative videos and detailed explanatory documents, describing the necessary processes.

Fig. 7. Overview of the mobile cadastral application user interface, when "MANUAL SELECTION" is chosen (left to right): (a) descriptive information insertion tool "ADD INFORMATION" and document attachment or photo capture tools (b) necessary proprietary (LADM-based) information, filled in by the user (c) geometric editor which comprises all the available geometric tools and operations & land parcel digitization tool (d) building's unit digitization tool, and (e) data storage tool, in the Server of ArcGIS Online.

The responsibilities of the leaders also include the collection of the available cartographic basemaps or/and BIM data, the utilization of the necessary pre-processing steps for their insertion into the cadastral server, and therefore, for their usage by the cadastral mobile application. Next, the 3D cadastral surveys are performed by the right holders through the cadastral mobile application. Each right holder, identifies his/hers property on the available basemap or selects it on the available BIM/IFC representation, and insert all the necessary cadastral information. 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 right holders.

In the fifth and last phase, the evaluation and control of this database

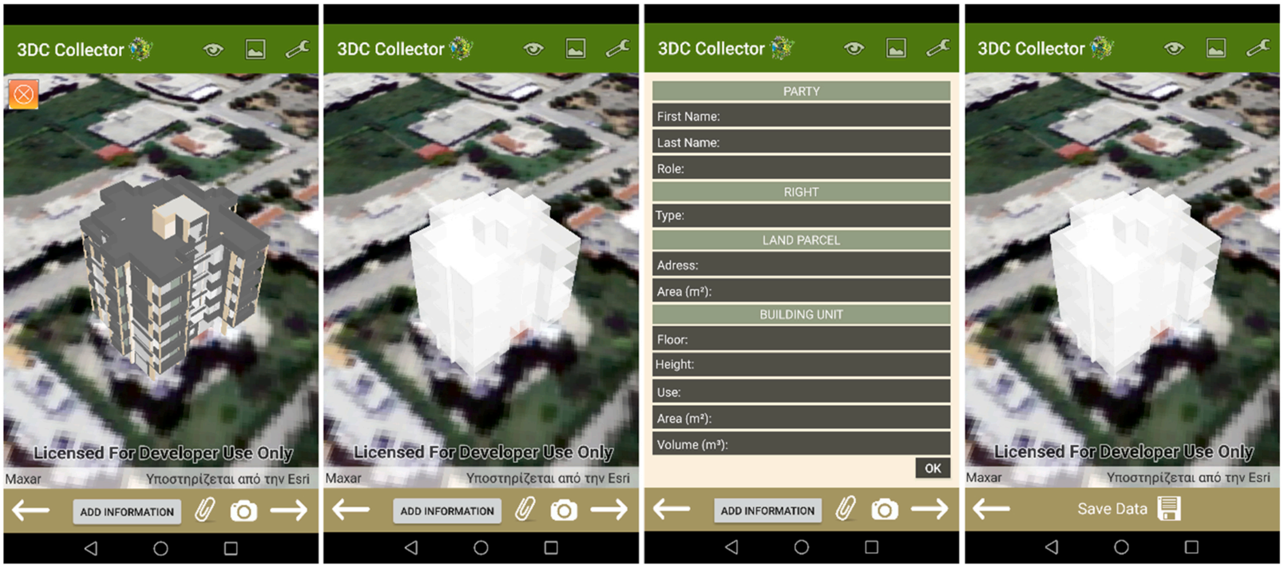

Fig. 8. Overview of the mobile cadastral application's user interface, when "BIM SELECTION" is chosen (left to right): (a) descriptive information's insertion tool "ADD INFORMATION" and documents attachment or photos capture tools & representation of BIM in LoD3, using the "BIM View" tool. (b) representation of BIM in LoD1 (legal spaces), closing the BIM View (c) necessary proprietary (LADM-based) information, filled in by the user (d) data storage tool, in the Server of ArcGIS Online.

is conducted by cross checking the legal documents with the declared crowdsourced data and publishing. 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 right holders in the initial data should be accepted (Fig. 9). Next, the preliminary cadastral data is published at the NCMA's offices, while then the examination of objections, the decisions on objections and the necessary correction of data, is compiled. By the end of the phase, the Initial/First Registrations in the 3D Hellenic Cadastre will be achieved.

6. Practical experiment

To investigate the effectiveness of the proposed 'two-route' crowdsourced approach and the developed technical framework, a practical experiment examining two different data availability cases, is implemented. The practical experiment deals with two multi-storey buildings, located in an urban area of the city of Athens, Greece (Fig. 10). For each of the buildings a different type of geospatial data was provided, thus differentiating the method which should be followed in order to proceed with the 3D cadastral registration procedure. Despite the selected registration method, the main objective of this process was to identify each property unit and record some basic descriptive information about the rights and the right holders, utilizing the developed mobile application.

6.1. Data

Building 1 and Building 2, are two neighboring multi-storey buildings, distinguished by various overlapping property units and common spaces of complex geometry. For each building different registration background types are assumed to be available, in order to proceed with the 3D cadastral registration. For Building 1, an orthophoto of the test area at a scale of 1:1000 (Fig. 10) and the georeferenced floor plans of the underground floor, the ground floor and the rest five (5) floors above the ground, at a scale of 1:100 (Fig. 11), were utilized. For Building 2, an existed BIM was utilized (Andritsou et al., 2022).

For the creation of the BIM, the Autodesk's Revit software was selected, while a set of available georeferenced floor plans were utilized as reference data. After the creation of the physical spaces in LoD3, the legal spaces of Building 2 were generated, utilizing the Area and Schedule function of Revit. With the Area tool the identification of the 2D boundaries for each 3D legal space is enabled. As the proper identification of the exact location of the legal boundaries along the horizontal and vertical structural elements of buildings varies according to the current legislation of each country, we realized certain assumptions based on the Greek legislation. Thus, we considered as boundaries the conceivable lines passing through:

- the middle of the floors, walls and ceilings, in cases of proximity of the property unit with another individual property unit or common space.
- the exterior faces of walls, floors and ceilings in the cases where the respective structural element is adjacent to the exterior environment.

Furthermore, the generated 3D legal spaces are enriched further with the necessary semantic information concerning the property's RRRs, based on the developed LADM-based DBMS schema. Finally, the created legal spaces are matched with the IfcSpace entity in the exported IFC model, which was selected as exchange model in order to translate the BIMs 3D spatial information into the ArcGIS platform.

6.2. Pre-processing steps

Aiming the available data to be utilized by the developed mobile application, a set of pre-processing steps are required, for both their configuration as well as their insertion into the Cloud of ArcGIS Online.

6.2.1. Orthophoto and floor plans

As the provided orthophoto and the floor plans are already georeferenced, there are no much processing steps to be followed. In order these cartographic basemaps to be uploaded to the Cloud of ArcGIS Online, they are first inserted into the ArcGIS Pro environment and therefore they are published as Web Map Layers into the Server ArcGIS Online. Thus, they can be further retrieved and utilized from the developed mobile application for the implementation of 3D crowdsourced cadastral surveys.

6.2.2. BIM data

Unlike the orthophoto and the floor plans, the pre-processing steps

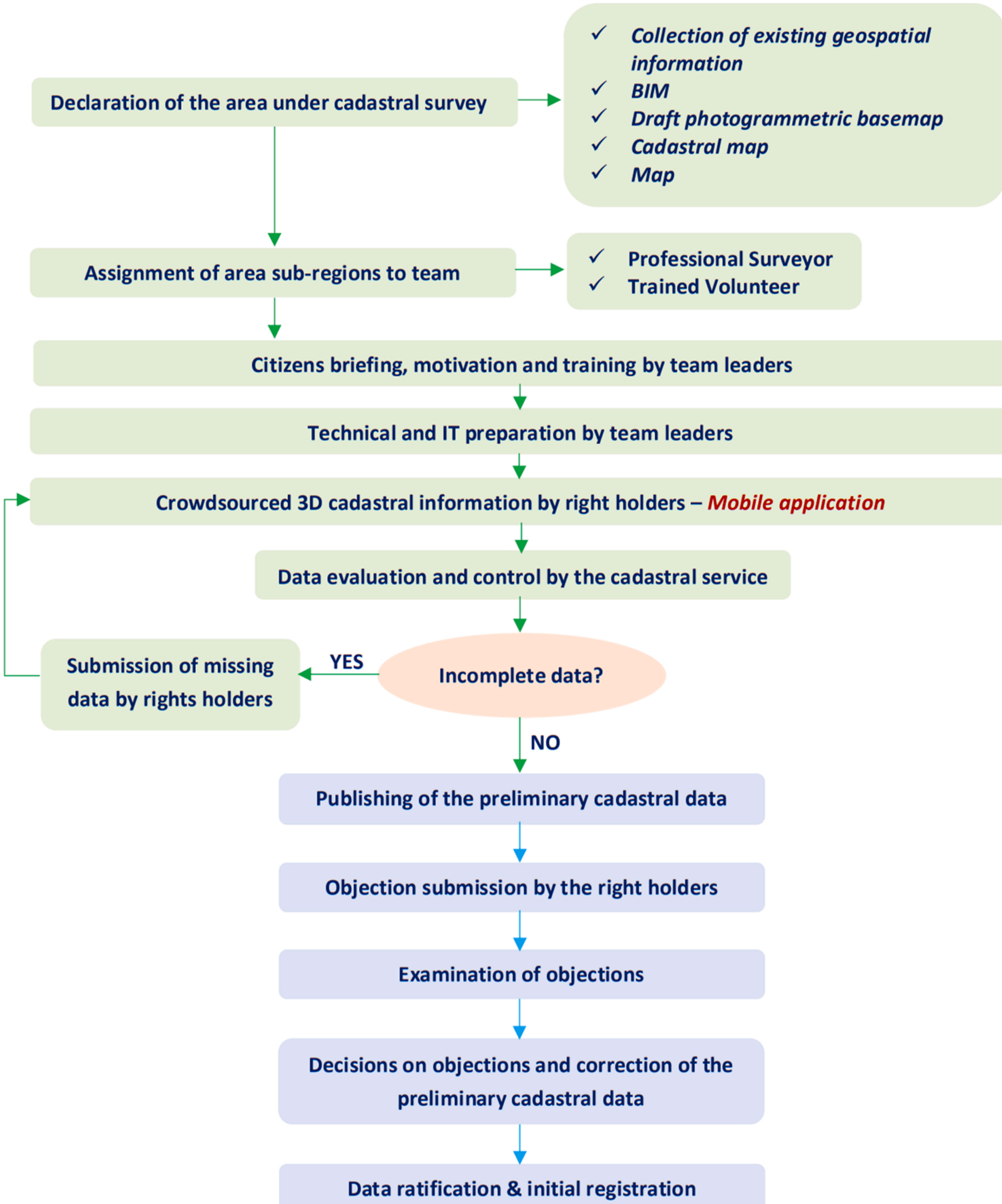

Fig. 9. Proposed crowdsourcing methodology for 3D cadastral surveys in Greece.

concerning BIM data are more complicated. Once the BIM is exported from Revit software, the generated IFC model is imported into the ArcGIS Pro environment, utilizing quick import tool from Data Interoperability Toolbox. Thus, the IFC model is translated into a file geodatabase and then the IfcSpace entity is directly connected with the BIM_BuildingUnit3D class of the developed LADM-base geodatabase, which is now enriched with the necessary geometric information concerning the cadastral legal spaces. It should be noted, that despite performing all the necessary steps during the development of BIM with Revit software, its georeference is not properly maintained when IFC is inserted into ArcGIS Pro environment. This is a common issue in the context of BIM–GIS integration. For this particular study, the IFC2×3 version is utilized, which despite the embedded spatial reference information, mismatches may occur when importing the model to a GIS environment (Zhu and Wu, 2021). However, this issue is solved in the IFC4 version by introducing a new entity that includes and maintains all the necessary elements for the geo-reference of the model (Gkeli et al., 2021b).

For the purpose of this study the model is horizontally aligned close to its correct position with a fixed offset of 12 cm, while its vertical alignment is incorrect, making it appear higher than its correct position. To overcome this problem, the model is moved to its correct horizontal position utilizing the editing tools of ArcGIS Online. By the end of this phase, the developed LADM-based geodatabase is uploaded to the Cloud of ArcGIS Online, so that it can be utilized for the implementation of 3D crowdsourced cadastral surveys through the developed mobile

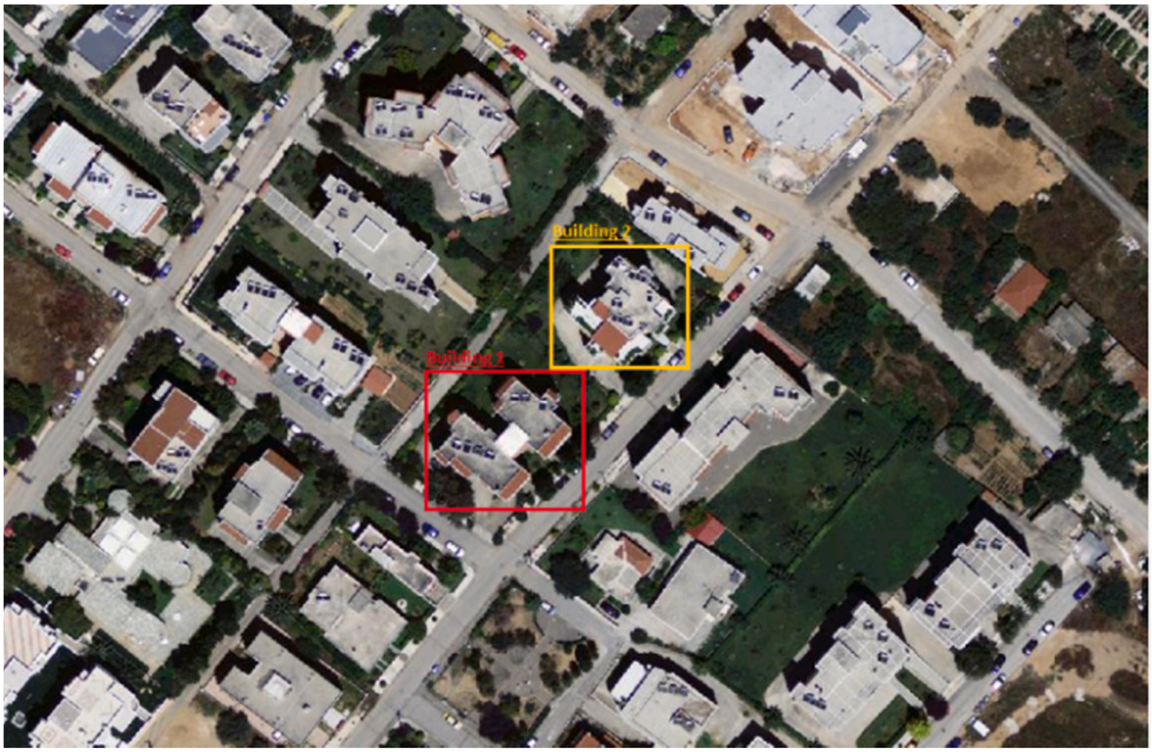

Fig. 10. Orthophoto of the test area at the scale of 1:1000, depicting the studied buildings; Building 1 (in red) and Building 2 (in orange).

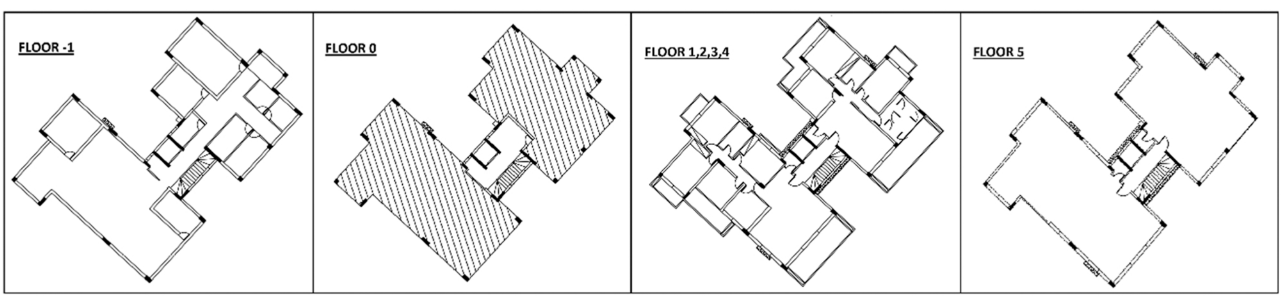

Fig. 11. Floor plans of the underground floor, the ground floor, first, second, third and fourth (identical) floors and fifth floor of Building 1, at the scale of 1:200 (Andritsou et al., 2022).

application.

6.3. Implementation and results

For the practical implementation the proposed crowdsourced methodology is followed. A team of volunteers consisted of NTUAs' students, are used as right holders in order to proceed with the 3D cadastral registration. As team leader a member of our research team is selected, in order to inform the volunteers about the objectives of this research project and train them regarding the functions of the developed mobile application and the technical preparation. Each one of the volunteers is responsible for identifying a specific number of property units in both Building 1, utilizing the provided orthophoto and the floor plans; and in Building 2, utilizing the BIM; and therefore declare the necessary descriptive and geometric cadastral information through the developed mobile application. For this practical experiment, the descriptive information about the right holder (first name, last name, and type of right); and the property unit (address, area code, and use), are selected. Once the volunteers are familiarized with the mobile application the 3D cadastral registration process started. Although the GPS of the smartphones is usually beneficial in determining the user's position, it does not utilized in this practical experinment, as the positioning accuracy in the interior of the buildings was weak (3–6 m).

Based on which of the two buildings the current property unit is located, a different method is followed by the volunteers. Whichever method is selected, the volunteer's first step is to insert all the necessary descriptive and geometric cadastral information concerning their property.

- For the registration of the property units of Building 1, the "Manual Selection" is chosen. The volunteers must identify the boundaries of the land parcel, by selecting features (points) on the basemap (orthophoto), utilizing the digitazation tool. In cases where the land parcel's boundaries are not clearly recognized on the basemap, the geometric tool provided by the mobile application may also be utilized. Following a similar logic, the volunteers must select the floor basemap in which the property unit is located; and identify the property unit boundaries (outline). Finally, the volunteers save the data and complete the cadastral registration procedure for each of the property units of Building 1. An example of the described registration procedure, is illustrated in Fig. 12.

Fig. 12. Example of the recording process through the ”MANUAL SELECTION” option of the developed mobile application, including (from left to right): (i) the insertion of the adequate information, (ii) the digitized polygon describing the land parcel, (iii) the property unit to be registered, (iv) the degitized polygon describing the building unit, on the floor basemap, and (v) the declared building unit to be saved, in the Cloud of ArcGIS Online.

- For the registration of the property units included in Building 2, the ”BIM Selection” is chosen by the volunteers, as in this case BIM data are available. Through this *”route”* the volunteers follow a more simple sequence of procedural steps. By tapping on the BIM at the position where they assume that the desired property unit is located, the 3D volume presenting the legal space where the RRRs are assigned is highlighted. If the selected property is the desired one, the volunteer can proceed with the complition of the registration and save the collected data.

Once the volunteers collect all the required data and submit their declarations, the data and the 3D models are stored in the cloud of ArcGIS Online, updating the system with the new records. An example of the described registration procedure is presented in Fig. 13. It is noted that during the whole procedure the team leader was at the volunteers' disposal in order to resolve any questions that they may have.

Following this sequence of registration steps, the volunteers are now able to complete successfully the registration procedure. By utilizing the ”Manual Selection” option, the average duration of each property unit's registration is about 8–20 min, while through the ”BIM Selection” option the registration duration is reduced approximately to 7–14 min per property unit. The registration duration is strongly affected by several factors, such as the familiarity of the volunteer with the mobile application, the volunteers' perception regarding their position into the 3D scene, their technical skills, the complexity of the property unit's geometry, the location of the property in the BIM as well as the technical and qualitative characteristics of the mobile device utilized by the volunteer. An old and underfunctioning mobile device, makes data capturing and data storage processes particularly difficult.

The collected cadastral data are correctly assigned to the 3D cadastral legal objects represented both through the BIM and the generated 3D property models (LoD1) (Fig. 14). Especially for the case of Building 1, some additional quality results are extracted regarding the accuracy of the collected geometric data. A comparison is conducted between the digitized property unit polygons of each building floor and the reference data. As reference data the vector floor plans are utilized. The results are satisfactory as no significant discrepancies are detected, as the average accuracy deviation between the compared datasets is 0.19 m and their

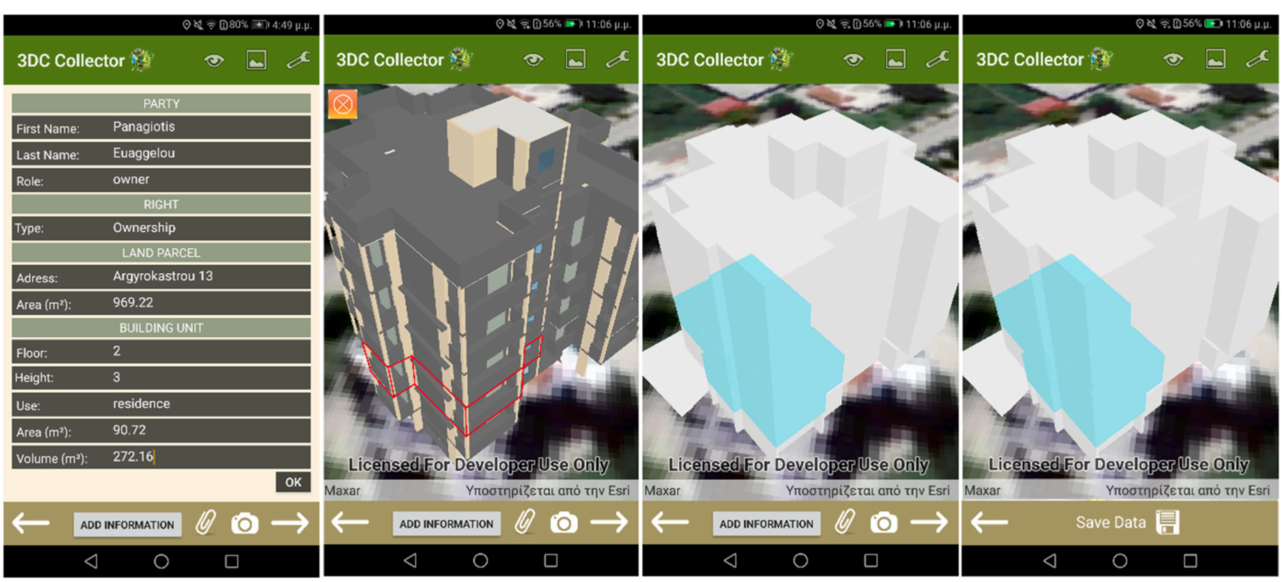

Fig. 13. Example of the registration process through the ”BIM SELECTION” option of the developed mobile application, including (from left to right): (i) the insertion of the necessary information concerning the right holder, the land parcel, the building and the building unit, (ii) the identification of the desired property (in red) through the visualization of LoD3, (iii) the selection of the desired property in LoD1, and (iv) the storage of the collected data in the Cloud of ArcGIS Online.

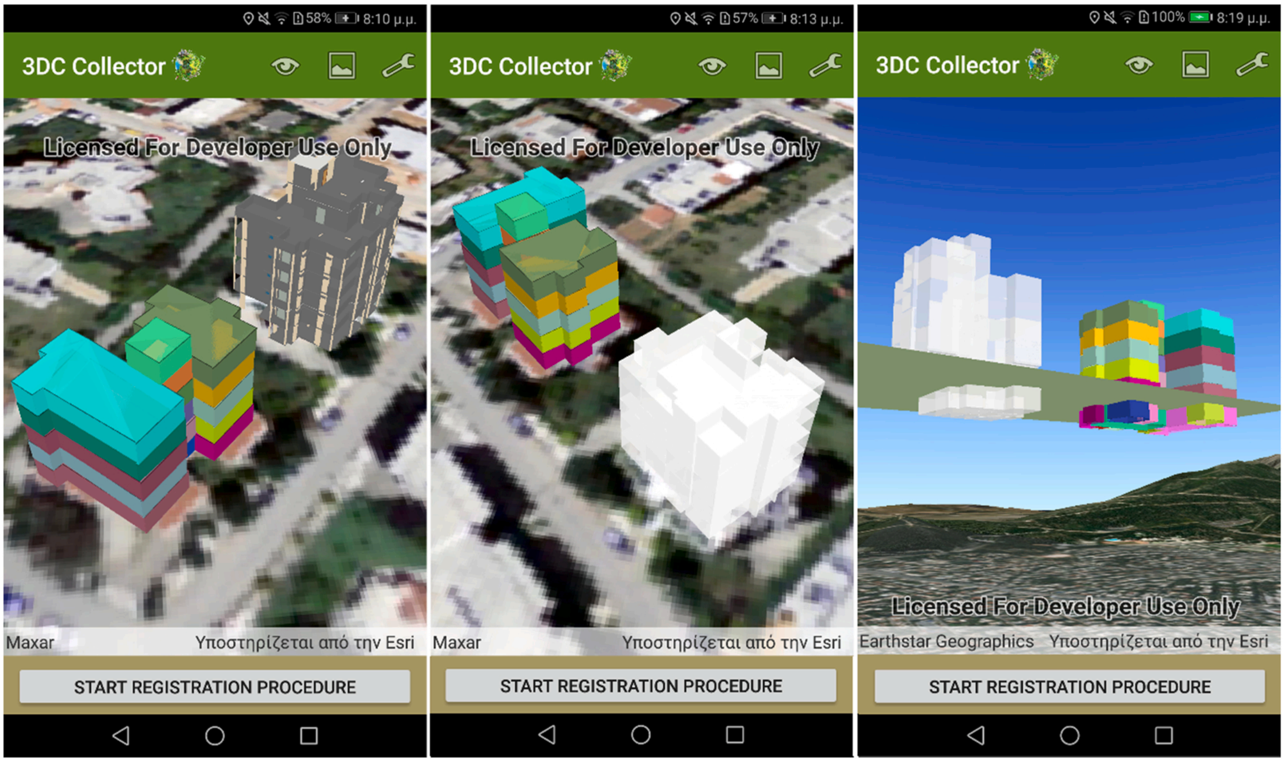

Fig. 14. The generated 3D property models of Building 1 and the BIM of Building 2 in LoD3 (right), the generated 3D property models of Building 1 and the BIM of Building 2 in LoD1 (middle), and the generated 3D property models of Building 1 and the BIM of Building 2 in LoD1, both above and below the ground surface.

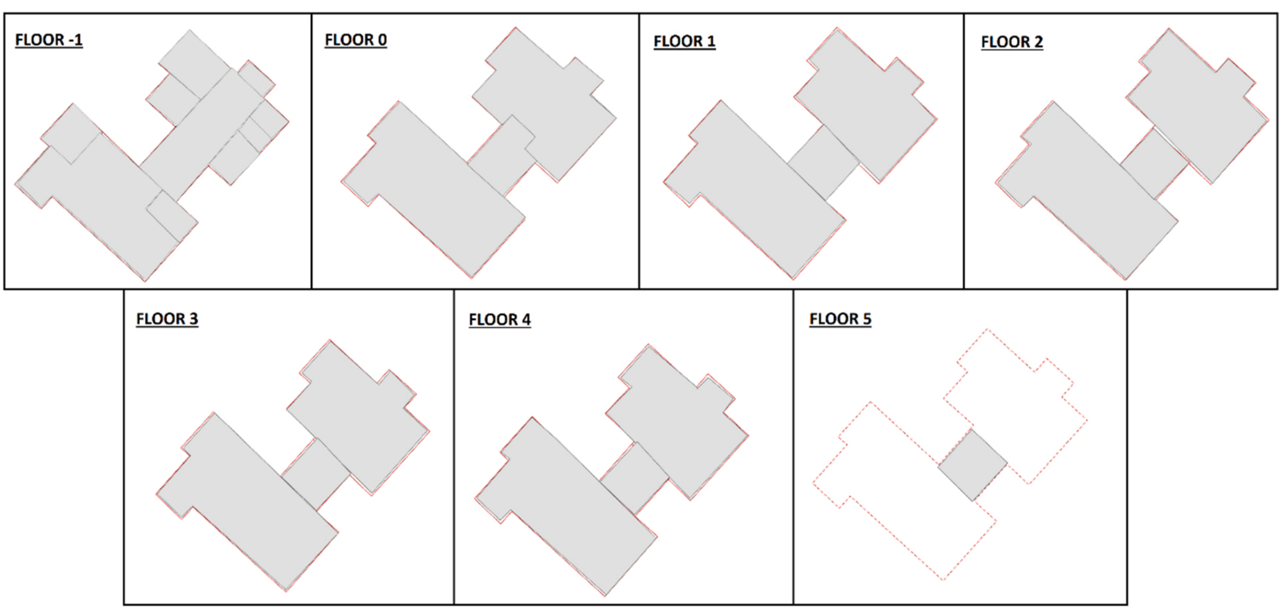

Fig. 15. Comparison between the digitized polygons (in solid gray) and the reference data (in red), for each one of Building's 1 floors.

maximum and minimum deviation is approximately 0.48 m and 0.01 m, respectively (Fig. 15). It is noted, that the maximum deviation refers to misidentification of interior building boundaries, seperating the private owned properties from the common spaces. The floor plans of Building 1 include some architectural peculiarities (e.g., roof tiles) that are incorrectly considered as structural elements of the building/boundaries. Finally, the generated 3D models are correctly positioned in 3D space, representing each property unit with a different color texture.

7. Discussion and Conclusions

The establishment of a 3D cadastral system able to represent and manage property rights in a uniform, standardized and reliable way, both above and below the land surface, is of great importance. Such system may support the government administration and provide an effective and transparent system for securing property's RRRs, facilitating property valuation, managing real estate markets in modern cities, as well as other necessary urban reforms.

The introduction of crowdsourcing techniques and low-cost modern IT tools in the formal Greek cadastral procedures has shown that the participation of right holders, who can better identify their own properties without errors, can minimize the time and costs of the cadastral surveys and more importantly it can eliminate the gross errors (Gkeli et al., 2016; Mourafetis et al., 2015). Besides 2D cadastral surveys, crowdsourcing has been also tested in 3D cadastral surveys, adding an alternative perspective to the initial development of the 3D Cadastre (Gkeli et al., 2018; Gkeli et al., 2020a; b,c; Gkeli et al., 2021a; Gkeli and Potsiou, 2021b). Recent research has shown that the utilization of the available geospatial infrastructure (orthophotos, cadastral maps, architectural floor plans, aerial photos etc.), in combination with parametric modelling techniques, or existing geospatial 3D data sources generated in other application areas, such as BIM data, may be of significant importance for the initial implementation of a reliable crowdsourced 3D cadastral system.

Considering these findings, it can be argued that the combined use of all the possible 2D or 3D data sources into a single solution, can further accelerate the required cadastral processes and lay solid foundations for the initial implementation of 3D Cadastre, both in the Greek territory but also in other countries, regardless of whether they have already established a complete 2D cadastre or not. As proved by the test implementation, the integration of multiple data sources into a unified registration background is feasible, both methodologically and technically. However, an important aspect affecting the uniform integration of BIM data in the cadastral process, is the identification of the exact location of properties boundaries, following a standard framework. As turned out, there is no clear definition regarding the exact position of property boundaries in the Greek law (i.e. in the middle of the wall, exterior/interior face). Only a general description of their conceivable extend is available, which usually is determined more precisely through a notarial deed. However, in recent literature there are several approaches regarding this matter, that can be followed. The development of a commonly accepted standard concerning the imposition of a uniform way for defining the location of the properties boundaries, is needed, facilitating the inclusion of BIMs in 3D Cadastre.

During the proposed process, the right holders may select the registration option that better fits their own situation, and proceed with the cadastral procedure, as determined by the mobile application. According to the volunteers' evaluation, the registration process using BIMs is relatively easy, increasing the receptivity of the volunteers to perform and complete the necessary steps for the implementation of the 3D crowdsourced cadastral surveys. Simultaneously, the registration process through the manual option is relatively simple, without demanding any certain level of 3D modelling skills in order the volunteer to contribute to the registration procedure. Nevertheless, the effectiveness of the proposed technical solution is strongly influenced by the ability of the user/volunteer to manipulate the developed cadastral mobile application. In this particular test no major problems occurred, as the users/volunteers were young surveyors with advanced digital skills (engineering or technical skills), and they were well informed about the use of smart phones. However, as it was proven at earlier stages of our research such mobile applications or even more complicated mobile applications can be also managed by older people with limited digital skills (Gkeli et al., 2020b). Through proper training of the right holders and real-time support from the team leaders, the effectiveness and reliability of the proposed procedure will be increased and assured. Furthermore, the recruitment and commitment of the right holders, is further strengthened by the fact that they benefit through this participatory cadastral process, as they safeguard their property rights, without having to be burdened with additional fees. Also, the motivation and activation of rights holders may be enhanced through methods such as gamification (Apostolopoulos et al., 2018). For example, the imposition of a tax reduction in exchange for their participation in such a cadastral project, can increase the reliability of the process.

Furthermore, the adoption of LADM international standard in order to structure the collected data, consists a valuable feature of the proposed technical solution. The developed framework aims to save time and funds, simplify the registration process, enable communication between the involved parties, data exchange, and increase the reliability of the collected data. The selection of a mobile application as the main data capturing tool, is helpful as a mobile device allows the right holders to move throughout the property using the GPS sensor and be oriented in the 3D space and the 3D visual environment simultaneously. The developed mobile application enables the collection of the required data in a short time frame, with the registration of each property unit to fluctuate between 8 and 20 min through the" Manual Selection" option, and 7–14 min through the" BIM Selection" option, which is hard to be achieved with traditional cadastral surveying procedures. Nonetheless, in such crowdsourced projects there is a trade-off between time and achieved accuracy. According to the test implementation, the recording procedure is fast with an average accuracy deviation of RMSExy = 0.19 m and a maximum of 0.48 m. The achieved accuracy may not meet high accuracy requirements; however, it satisfies the current accuracy specifications of the Greek Cadastre which for urban areas is 0.71 m (RMSExy). Furthermore, the developed technical solution provides a reliable and valuable representation of the 3D cadastral objects. Following the "Manual Selection" option, the 3D property unit models are generated automatically through the utilization of parametric 3D modelling techniques (Model-driven approach), producing geometrically accurate and correctly positioned 3D models, despite the known difficulties in 3D modeling techniques that usually constitute a time consuming and tedious processes. Besides the "Manual Selection" option, the "BIM Selection" option provides even more accurate results, as exploits the rich geospatial content of BIMs. Either way, each 3D model included in the developed LADM-based cadastral database, is accompanied by the corresponding descriptive information, facilitating any post-processing and querying procedures, useful in various applications.

So far, we can safely state that the first results of the developed technical solution are quite promising. The proposed approach may constitute a potential solution and set the basis for the initial implementation of a 3D cadastral system in Greece; but may be also adopted by other countries, with some minor diversifications, speeding up the processes and reducing the financial requirements for the initial implementation of 3D Cadastres. However, there are still plenty of other issues that need to be further investigated in order this venture to be fully functional. As a next step of this research, the investigation and identification of the different types of legal objects will be carried out, in order to investigate in detail, the weaknesses and challenges of the proposed technical framework and to proceed with the necessary corrections. Once the technical issues are identified a larger-scale implementation under real circomstuncies will be implemented in order the impact of this solution, the influencing factors affecting the data collection process and their quality, to be determined. Furthermore, the authentication and authorization system, the reward policy, the penalty policy in cases where right holders intentionally submit false data etc. should be also investigated. Since the use of mobile devices and crowdsourced data in 3D cadastral surveys is a newly emerging field, it is clear that much more issues need to be clarified and studied.

Data Availability

The data used for this research is not available online.

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