National Technical University of Athens

School of Rural, Surveying and Geoinformatics Engineering

Automated Urban Modeling and Crowdsourcing Techniques for 3D Cadastre

Doctoral Dissertation

Maria Gkeli

National Technical University of Athens

School of Rural, Surveying and Geoinformatics Engineering

Automated Urban Modeling and Crowdsourcing Techniques for 3D Cadastre

Doctoral Dissertation

Maria Gkeli

Dipl. Rural, Surveying and Geoinformatics Engineer, NTUA

Supervisor:

Charalabos Ioannidis, Professor, NTUA

Athens, May 2023

Advisory Committee:

Charalabos Ioannidis, Professor, NTUA, Supervisor

Chryssy Potsiou, Professor, NTUA

Nikolaos Doulamis, Professor, NTUA

Examination Committee:

Charalabos Ioannidis, Professor, NTUA, Supervisor

Chryssy Potsiou, Professor, NTUA

Nikolaos Doulamis, Professor, NTUA

Vyron Antoniou, Assistant Professor, Hellenic Army Academy

Apostolos Arvanitis, Professor, AUTH

Efi Dimopoulou, Professor, NTUA

Olga Georgoula, Professor, AUTH

Εθνικό Μετσόβιο Πολυτεχνείο

Σχολή Αγρονόμων & Τοπογράφων Μηχανικών - Μηχανικών Γεωπληροφορικής

Αυτοματοποιημένες Τεχνικές στη Μοντελοποίηση του Χώρου με Δεδομένα Πληθοπορισμού για το 3Δ Κτηματολόγιο

Διδακτορική Διατριβή

Μαρία Γκέλη

Διπλωματούχος Αγρονόμος & Τοπογράφος Μηχανικός και Μηχανικός Γεωπληροφορικής, ΕΜΠ

Επιβλέπων Καθηγητής:

Χαράλαμπος Ιωαννίδης, Καθηγητής ΕΜΠ

Αθήνα, Μάϊος 2023

Τριμελής Συμβουλευτική Επιτροπή:

Χαράλαμπος Ιωαννίδης, Καθηγητής ΕΜΠ, Επιβλέπων

Χρυσή Πότσιου, Καθηγήτρια ΕΜΠ

Νικόλαος Δουλάμης, Αναπληρωτής Καθηγητής ΕΜΠ

Επταμελής Εξεταστική Επιτροπή:

Χαράλαμπος Ιωαννίδης, Καθηγητής ΕΜΠ, Επιβλέπων

Χρυσή Πότσιου, Καθηγήτρια ΕΜΠ

Νικόλαος Δουλάμης, Καθηγητής ΕΜΠ

Βύρων Αντωνίου, Επίκουρος Καθηγητής, ΣΣΕ

Απόστολος Αρβανίτης, Καθηγητής ΑΠΘ

Όλγα Γεωργούλα, Καθηγήτρια ΑΠΘ

Έφη Δημοπούλου, Καθηγήτρια ΕΜΠ

The research was funded by a scholarship awarded by the Onassis Foundation, and the Hellenic Foundation for Research and Innovation.

To my parents, in their loving memory,

And to my beloved brother.

Acknowledgements

After almost six years of my doctoral studies I have to say that getting this PhD was a life-changing experience; full of challenges, self-doubts, intense moments, but also exiting, fruitful and enjoyable periods. Through this journey I had the opportunity to gain a lot of knowledge and the honor to collaborate with excellent scientists and make good friends. This is a great treasure that I will cherish not only in my future career but also in my whole life. In this section I would like express my immense gratitude to all those persons who have given their invaluable support and assistance.

First and foremost, I am extremely grateful to my supervisor, *Professor Charalabos Ioannidis* for his invaluable advice, guidance, continuous support, encouragement and patience during all the stages of my PhD studies. From the beginning, he trusted me and gave me more strength and spirit to complete this research. With his invaluable advice he helped me manage my anxiety and focus on my goals. He gave me the opportunity to participate in research activities and specifically in the research program "Cargo Bikes and Drones" and work alongside him being an incredible mentor. His valuable recommendations and key observations in all publications have supported this research both scientifically and technically. His immense knowledge and plentiful experience have encouraged me in all the time of my doctoral study and daily life.

Professor Chryssy Potsiou for her participation in the advisory committee, her professional advice, methodical supervision, encouragement and motivation that she gave me during my doctoral study. She showed me belief, shared her innovative ideas and encouraged me to engage in a still unexplored field of research. She helped me to improve and evolve not only academically but also personally. Her valuable remarks and suggestions were decisive for the quality upgrade and completion of the dissertation.

Professor Nikolaos Doulamis, for his participation in the advisory committee, his important scientific and technical proposals and the excellent cooperation. He guided me and opened new horizons for me on how the science of electrical engineering and computer engineering can contribute to the science of surveying engineering.

In addition, I would like to thank the executives of Marathon Data Systems, *Mr. John Kontos and Grigoris Kontos,* who introduced me to the world of Geographic Information Systems and offered me access to software and data, facilitating the progress of the research.

Also, I would like to thank all the other members of the examination committee for their willingness to participate in the examination of this doctoral dissertation.

In addition, I would like to thank all my colleagues and friends in the Department of Topography and especially in the Laboratory of Photogrammetry for their moral and technical support as well as for all the valuable advice throughout my doctoral studies. Especially, I would also like to thank *Sofia Soile, MSc Surveyor Engineer* at the Laboratory of Photogrammetry, for the time she devoted to providing me with all the necessary data and her technical support whenever was needed.

I would like to express my sincere and deepest thanks to *Onassis Foundation* and the *Hellenic Foundation for Research and Innovation,* who trusted me, believed in me and financially supported me throughout my doctoral studies, making my doctoral research come alive. With this valuable contribution, they allowed me to integrally carry out and complete the research and achieve my goals. A big thank you from the bottom of my heart.

Finally, I would like to thank my friends and family for their unwavering support throughout this journey. I want to give my deepest appreciation to my brother, *George Gkelis*, for his unwavering support at every stage of my life and throughout my studies till this day. Without his faith in my potential, his support, his tremendous understanding and encouragement all these years, it would have been impossible for me to complete my doctoral studies and accomplish my dreams.

Finally, but the most importantly, I would like to thank my parents for all the sacrifices they made for my brother and myself and for the unconditional love, care, solid supplies, advice and life lessons they provided for us to become the people we are today. *Although you are no longer with us, your presence will accompany us forever. I hope you see us from up there and be proud of what we have accomplished so far in our lives.*

To all, my deepest and most heartfelt gratitude.

Maria Gkeli

Publications

International Peer-Reviewed Journal Articles

Gkeli M., Potsiou C. (2023). 3D crowdsourced parametric cadastral mapping: Pathways integrating BIM/IFC, crowdsourced data and LADM. *Land Use Policy*, 131, 106713.

Potsiou C., N. Doulamis, N. Bakalos, **M. Gkeli**, C. Ioannidis, S. Markouizou, S. (2022). A Prototype Machine Learning Tool Aiming to Support 3D Crowdsourced Cadastral Surveying of Self-Made Cities. *Land*, 12(1), 8.

Potsiou C., C. Ioannidis, S. Soile, S. Verykokou, **M. Gkeli**, M. Filippakopoulou (2022). A Technical Tool for Urban Upgrading: An Application for Cultural Heritage Preservation and Planning for Affordable Housing. *Land*, 11(8), 1197.

Gkeli M., C. Potsiou, S. Soile, G. Vathiotis, M.E. Cravariti (2021). A BIM-IFC Technical Solution for 3D Crowdsourced Cadastral Surveys Based on LADM. *Earth 2021*, 2(3): 605-621. https://doi.org/10.3390/earth2030035.

Gkeli M., C. Potsiou, C. Ioannidis (2019b). A technical solution for 3D crowdsourced cadastral surveys. *Land Use Policy*, 98, https://doi.org/10.1016/j.landusepol.2019.104419.

Gkeli M., C. Potsiou, C. Ioannidis (2019a). Crowdsourced 3D cadastral surveys: looking towards the next 10 years. *Journal of Geographical Systems*, 21(359), https://doi.org/10.1007/s10109-018-0287-0.

Apostolopoulos K., **M. Gkeli**, P. Petrelli, C. Potsiou, C. Ioannidis (2018). A new model for Cadastral Surveying using Crowdsourcing. *Survey Review*, 50(359): 122-133, doi:10.1080/00396265.2016.1253522.

Gkeli M., C. Ioannidis, C. Potsiou (2017b). The potential use of VGI for 3D cadastre surveys. *Coordinates magazine*, XIII(10): 14-19.

Gkeli M., C. Ioannidis, C. Potsiou (2017a). 3D Modelling Algorithms and Crowdsourcing Techniques. *Coordinates magazine*, 13(9): 7-14.

International Peer-Reviewed Conference Papers

Potsiou C., C. Ioannidis, S. Soile, A.M. Boutsi, R. Chliverou, K. Apostolopoulos, **M. Gkeli**, F. Bourexis (2023). Historic Walking Trails in the Holy Site of Meteora. In: *3rd TMM_CH International Conference on "Transdisciplinary Multispectral Modelling and Cooperation for the Preservation of Cultural Heritage: Recapturing the World in Conflict through Culture, promoting mutual understanding and Peace"*, 20-23 March 2023, Athens, Greece.

Evangelou T., **M. Gkeli**, C. Potsiou (2022). Building digital twins for smart cities: a case study in Greece. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., 10.*

Andritsou D., **M. Gkeli**, S. Soile, C. Potsiou (2022). A BIM/IFC–LADM solution aligned to the Greek legislation. *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, 43, pp. 471-477.

Gkeli M., C. Potsiou (2021). Linking LADM with BIM/IFC standards for mobile-based 3D Crowdsourced Cadastral Surveys. In: *7th International FIG 3D Cadastre Workshop*, 11-13 October 2021, New York, USA.

Gkeli M., C. Potsiou, C. Ioannidis (2021). BIM data as Input to 3D Crowdsourced Cadastral Surveying—Potential and Perspectives. In: *FIG e-Working Week 2021*, 20–25 June 2021.

Potsiou C., N. Doulamis, N. Bakalos, **M. Gkeli**, C. Ioannidis (2020). Indoor localization for 3d mobile cadastral mapping using machine learning techniques. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., VI-4/W1-2020, pp. 159–166. https://doi.org/10.5194/isprs-annals-VI-4-W1-2020-159-2020, 2020.

Gkeli M., C. Potsiou, C. Ioannidis (2020). Design of a crowdsourced 3D cadastral technical solution. *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. XLIII-B4-2020, 2020 XXIV ISPRS Congress (2020 edition), pp. 269-276. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-269-2020.

Gkeli M., C. Potsiou, C. Ioannidis (2020). Mobile Crowdsourcing in 3D Cadastral Surveys: Exploring the Public's' Reaction and Data Quality. In: *FIG Working Week 2020 "Smart Surveyors for Land and Water Management"*, Amsterdam, Netherlands, 10-14 May 2020.

Gkeli M., C. Ioannidis (2018). Automatic 3d reconstruction of buildings roof tops in densely urbanized areas. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.,* XLII-4/W10, pp. 47-54. https://doi.org/10.5194/isprs-archives-XLII-4-W10-47-2018.

Gkeli M., C. Potsiou, C. Ioannidis (2018). LADM-based Crowdsourced 3D Cadastral Surveying – Potential and Perspectives. In: *6th International FIG Workshop on 3D Cadastres*, Delft, Netherlands, 2-4 October 2018.

Gkeli M., C. Ioannidis, C. Potsiou (2017). VGI in 3D Cadastre: A Modern Approach. In: *FIG Commission 3 - Annual Workshop "Volunteered Geographic Information: Emerging Applications in Public Science*", Lisbon, Portugal, 21 p.

Gkeli M., C. Ioannidis, C. Potsiou (2017). Review of the 3D Modelling Algorithms and Crowdsourcing Techniques - An Assessment of their Potential for 3D Cadastre. In: *FIG Working Week 2017 – "Surveying the world of tomorrow – From digitalization to augmented reality"*, Helsinki, Finland, 23 p.

Gkeli M., K. Apostolopoulos, G. Mourafetis, C. Ioannidis, C. Potsiou (2016). Crowdsourcing and mobile services for a fit-for-purpose Cadastre in Greece. In: *SPIE, Fourth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2016)*, 9688(968817), doi:10.1117/12.2240835.

Abstract

The ever-increasing prevalence of multidimensional infrastructures in the urban environment raises the complexity of land administration procedures and urban reforms, introducing new challenges to the recording, modeling, management and visualization of the spatial extent of vertically stratified man-made objects, and especially buildings. Three-dimensional (3D) city modeling appears to be a valuable tool for supporting the dynamic land management and governance of the multidimensional cities. The development and maintenance of an up-to-date semantically enriched 3D building models database, enhances these perspectives, while providing useful information for several applications such as urban planning, land administration, 3D Cadastre, Digital Twins (DT), security applications, navigation and risks management.

With the rapid globalization of urbanization, great pressure is exerted 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. Buildings with several uses referred to the same building footprint, present a complex equation of overlapping interests which must be properly managed. In most countries, 3D property units are registered utilizing two-dimensional (2D) documentation and textual description. This approach has several limitations as it is unable to represent the actual extent of complicated 3D property units in space. Incorrect registrations, mistaken declarations, misunderstandings and multiple disputes concerning these property rights, are only some of the consequences of the poor management of the increasing multidimensional property rights. The sustainable management of large and mega cities requires transparency and credibility in the determination of property rights at every level, bringing the 3D Cadastre into the spotlight. However, the considerable costs and required time, for traditional 2D and/or 3D cadastral surveys prevent the completion of property registration and the well-functioning of property markets in several countries. Especially for the less-developed regions time and costs for the 3D cadastral data collection are prohibitive. To combat the challenge of 3D Cadastre establishment and maintenance, both in the developed and the developing world, more innovative and automated methods are needed. To meet the 2030 United Nations (UN) Agenda Sustainable Development Goals (SDGs) a Fit-For-Purpose (FFP) implementation methodology for a 3D cadastral system should be designed using modern low-cost Information Technology (IT) tools, UAVs, mobile services and crowdsourcing techniques for the 3D cadastral data acquisition; adopting international standards, such as the Land Administration Domain Model (LADM) standard, for data modelling; and introducing automation in data management and 3D visualization.

This research aims to develop methodologies and algorithms of photogrammetry and computer vision, for the automatic, affordable, fast and reliable generation of 3D semantically-enriched building models, focusing on the area of 3D Cadastres. This thesis tends to exploit the current research trends, innovative methods and modern technologies in order to develop a technical tool and a methodology for the initial data acquisition, management, maintenance, 3D modeling and visualization of cadastral objects, and establish a more generalized framework that is adjustable to the available geospatial infrastructure and financial situation of each country, including even regions that still lack a 2D land registry. This dissertation is in line with the global efforts aimed at developing 3D Cadastres and establishing a common standard for modeling cadastral information through LADM.

This thesis presents the perspectives of the potential use of crowdsourcing techniques for the collection of 3D spatial and descriptive data through modern IT tools and technologies,

while attempts to introduce automation into the spatial data processing procedures, aiming to produce reliable 3D models directly by non-experts, fast and affordably. The research unfolds following three main stages: (i) literature review, (ii) methodology and technical aspects development, and (iii) practical documentation. Initially, a literature review is conducted that examines the recent developments in 3D reconstruction techniques, methods and algorithms, as well as the experience gained from using crowdsourced data for 3D buildings reconstruction. Then, the potentials of using this experience to design a low-cost technical framework for the implementation of 3D cadastral surveys in urban and suburban areas is further examined. Finally, the developed methodologies, techniques, algorithms and software are presented followed by the main conclusions, findings and suggestions of the research.

This thesis is structured in eight (8) chapters, which respond to the aim of the research. Chapter 1 provides the outline of the study along with some background information identifying the existing deficiencies and gaps that consisted the main motivation for the elaboration of this dissertation. Moreover, the research objectives as well as the main innovations of the research are given in separate keynotes.

Chapter 2, delves into the topic of 3D Cadastre. Of the three development stages of 3D Cadastres, this dissertation mainly focuses on the technical stage. It examines several international efforts concerning the actual or experimental implementation of a 3D cadastral system; and, studies the findings and prospects of recent scientific meetings, academic studies and pilot projects related to 3D Cadastres. The main concept and features of the international standard of LADM are presented, with greater emphasis on its three-dimensional aspect, namely the definition of geometry and the visualization of the 3D spatial units. In addition, a number of international paradigms of country-level LADM-based profiles are selected and presented; and, several investigations trying to establish a link between LADM and commonly used technical data models, such as CityGML, IndoorGML, BIM/IFC, LandXML, are examined. The lack of connection to commonly accepted physical models is a significant shortcoming of LADM which should be addressed in a future upgrade of the international standard.

Chapter 3, provides a classification of the current 3D data acquisition methods and their products, which are commonly used in 3D building reconstruction procedures, while then presents a literature review of the state-of-the-art 3D reconstruction methods, techniques and algorithms. The research indicated that 3D buildings reconstruction methods can be categorized into three main categories: (i) Model-driven methods, (ii) Data-driven methods, and (iii) Hybrid methods. Traditionally, remote sensing imagery and/or laser scanning data are preferred for 3D reconstruction. However, the latest technological advances in data acquisition and computing systems have created the right conditions for the utilization of images captured through low-cost devices and crowdsourcing techniques, reducing the costs of the overall procedure. The choice of the most appropriate reconstruction method depends on several parameters related to the scale, the type of studied object or scene, the type of initial data, the required accuracy of the final product, the available funding, etc.; proving that there are several alternatives to proceed with 3D modeling, depending on the requirements of the application.

Furthermore, two different methodologies for the automatic detection, extraction and/or reconstruction of buildings are developed and presented. First, a methodology for the detection and reconstruction of noisy buildings' roof tops from geo-referenced point clouds, using photogrammetric techniques is presented. Then, a methodology for the detection, extraction and vectorization of buildings outlines from geo-referenced aerial imagery using deep learning techniques, is introduced. The data produced through the developed methodologies, are valuable for a wide variety of applications, such as 3D Cadastre which is studied in the current research, providing reliable metric information in a short time frame. Nevertheless, the required time, the economic and computational costs as well as the generation of complex surfaces do not favor the immediate and cost-effective development of 3D Cadastres. To this end, the recording of 3D cadastral objects seems to be benefited from more structured/parametric solutions, as mentioned in Chapter 2, which can be linked to Geographic Information Systems (GIS), such as cadastral systems.

Chapter 4 focuses on the contribution of Volunteer Geographic Information (VGI) and crowdsourcing in real-world 3D mapping applications. To evaluate the capabilities of the crowdsourced data in 3D modeling and specifically in 3D cadastral applications, the current approaches concerning the introduction of crowdsourcing in 2D cadastral surveys and 3D cadastral surveys are examined. Combining the findings of these approaches with the knowledge gained from Chapter 2, the advantages and disadvantages of 3D reconstruction methods when dealing with crowdsourced data are pointed out, concluding that parametric reconstruction methods consist the optimal choice. Following, the main parameters that influence: (i) the participation of citizens in crowdsourcing projects, (ii) the quality of crowdsourced data, emphasizing on accuracy; and, (iii) the usability of the data capturing applications, are discussed.

In Chapter 5 the developed methodology for the future implementation of 3D cadastral surveys is described and presented. The methodology tends to integrate the current research findings, lessons and trends and provide a flexible, viable and efficient model for the initial implementation of 3D crowdsourced cadastral surveys. The key features of the developed methodology include: (i) the briefing, motivation and training of the participants/right holders, (ii) the utilization of modern IT tools, emphasizing on mobile services, (iii) the establishment of an active cooperation between participants/right holders and professionals, and (iv) the incorporation of innovative techniques in data capturing and 3D modeling. Moreover, the potential alternative types of geospatial data that can be integrated in the developed methodological framework are identified. In addition to the traditional cartographic registration basemaps (orthophotos, cadastral maps, architectural floor plans etc.), the integration of physical-technical models, mainly the BIM, but also of innovative machine learning techniques for the implementation of Indoor cadastral mapping, are proposed. In this Chapter, a Greek paradigm trying to adopt the developed crowdsourced workflow in the Greek reality, is presented.

In Chapter 6 the overview of the architecture of the developed technical system is described and presented. The main parts of technical framework are composed from the *server-side* and the *client-side*. For the *server-side* a database schema introducing the specification of LADM ISO in the developed system, is realized. This venture aims to provide an integrated solution able to structure and manage different data types into the same platform. Moreover, for the *client-side* a mobile and a web application, with multiple functionalities are developed and presented. The developed cadastral applications aim to assist the implementation of 3D cadastral surveys, enabling the participation of the non-professionals into the cadastral registration and 3D modeling process. It is noted that 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.

In Chapter 7 the developed 3D crowdsourced technical framework is tested on a practical level. During this research ten practical applications are implemented, following the proposed methodological steps and utilizing different types of registration background. The background types are divided into three broad categories, based on their 2D or 3D form: (i) Cartographic basemaps, and (ii) BIM data. However, the simultaneous exploitation of both categories is also considered. The experiments explore the utilization of both m-services and web-services, emphasizing to the usage of mobile applications. The test areas are mainly concern densely populated urban areas, including also areas with sparse constructions. Based on the results of the case studies and the views of the participants, some key conclusions are drawn regarding the prospects, effectiveness, usefulness, reliability and quality of the developed technical framework.

Finally, Chapter 8 concludes this work by discussing the main findings concerning the previews Chapters, the developed 3D crowdsourced technical framework and the data quality, while also proposing some further thoughts and ideas for future research.

Ελληνική Περίληψη

Η ραγδαία ανάπτυξη και επικράτηση των πολυδιάστατων υποδομών στον αστικό χώρο, αυξάνει την πολυπλοκότητα των διαδικασιών διαχείρισης γης και των αστικών μεταρρυθμίσεων, εισάγοντας νέες προκλήσεις στις διαδικασίες καταγραφής, διαχείρισης, μοντελοποίησης και οπτικοποίησης των καθέτως στρωματοποιημένων κτιριακών δομών. Τα τρισδιάστατα μοντέλα πόλεων αποτελούν ένα πολύτιμο εργαλείο για την υποστήριξη των διαδικασιών διαχείρισης της γης και της διακυβέρνησης των αστικών περιοχών. Η ανάπτυξη και η συντήρηση μιας συνεχώς ενημερωμένης και σημασιολογικά εμπλουτισμένης βάσης τρισδιάστατων κτιριακών μοντέλων, ενισχύει αυτές τις προοπτικές, παρέχοντας παράλληλα χρήσιμες πληροφορίες για πολλές εφαρμογές, όπως εφαρμογές πολεοδομικού σχεδιασμού, διαχείριση γης, 3D Κτηματολογίου, Ψηφιακών διδύμων, εφαρμογών ασφάλειας, πλοήγησης, διαχείρισης κινδύνων κτλ.

Η ταχεία αστικοποίηση ασκεί μεγάλη πίεση στις υπάρχουσες αστικές δομές και χρήσεις γης, επιφέροντας αλλαγές στο κτιριακό απόθεμα των πόλεων. Έτσι, πραγματοποιείται ανάπτυξη πολλαπλών ιδιοκτησιακών ενοτήτων, οι οποίες διαθέτουν νομικές και φυσικές υποδιαιρέσεις τόσο οριζοντίως όσο και καθέτως της επιφάνειας του εδάφους. Η αποτύπωση αυτής της νέας πραγματικότητας θα πρέπει να υλοποιηθεί με ιδιαίτερη προσοχή, καθώς κάθε κτίριο απαρτίζεται από πολλαπλά και συνήθως επικαλυπτόμενα ιδιοκτησιακά συμφέροντα. Στις περισσότερες χώρες, οι τρισδιάστατες (3D) ιδιοκτησιακές μονάδες καταγράφονται χρησιμοποιώντας δισδιάστατη (2D) γεωμετρική τεκμηρίωση και λεκτική περιγραφή. Αυτή η προσέγγιση όμως, έχει αρκετούς περιορισμούς καθώς δεν είναι ικανή να αναπαραστήσει την πραγματική κατάσταση των 3D ιδιοκτησιακών μονάδων στον χώρο. Η αδυναμία σωστής διαχείρισης των όλο και αυξανόμενων πολυδιάστατων δικαιωμάτων ιδιοκτησίας οδηγεί σε λανθασμένες καταχωρίσεις και δηλώσεις ιδιοκτησίας, με αποτέλεσμα τη δημιουργία πολλαπλών διαφωνιών μεταξύ των εμπλεκόμενων μελών.

Η βιώσιμη διαχείριση των σύγχρονων πόλεων απαιτεί διαφάνεια και αξιοπιστία στον καθορισμό των δικαιωμάτων ιδιοκτησίας σε κάθε επίπεδο, φέρνοντας το 3D Κτηματολόγιο στο επίκεντρο. Παρόλα αυτά, το υψηλό κόστος και ο απαιτούμενος χρόνος για την υλοποίηση των δισδιάστατων ή/και τρισδιάστατων κτηματολογικών εργασιών ακολουθώντας παραδοσιακές τεχνικές και όργανα συλλογής δεδομένων, εμποδίζουν την ολοκλήρωση της καταγραφής των ακινήτων καθώς και την καλή λειτουργία των αγορών ακινήτων, σε πολλές χώρες. Ειδικότερα, στις λιγότερο ανεπτυγμένες χώρες, ο χρόνος και το κόστος συλλογής των 3D κτηματολογικών δεδομένων είναι απαγορευτικά. Προκειμένου να επιτευχθεί η υλοποίηση του 3D Κτηματολογίου, τόσο στον ανεπτυγμένο όσο και στον αναπτυσσόμενο κόσμο, χρειάζονται πιο καινοτόμες και αυτοματοποιημένες μέθοδοι. Για την επίτευξη των Στόχων Βιώσιμης Ανάπτυξης της Ατζέντας 2030 του ΟΗΕ, απαιτείται η σχεδίαση μιας εναλλακτικής μεθοδολογίας για την ανάπτυξη του 3D Κτηματολογίου, η οποία να προσαρμόζεται στον σκοπό της εκάστοτε εφαρμογής (Fit-For-Purpose), να χρησιμοποιεί σύγχρονα εργαλεία πληροφορικής και χαμηλού κόστους, να εκμεταλλεύεται τη διαθέσιμη χαρτογραφική υποδομή κάθε χώρας, τις κινητές υπηρεσίες και τεχνικές πληθοπορισμού για την απόκτηση 3D κτηματολογικών δεδομένων, να υιοθετεί διεθνή πρότυπα μοντελοποίησης δεδομένων, όπως το πρότυπο του Διεθνούς Μοντέλου Διαχείρισης Γης (LADM) και να ενσωματώνει την παράμετρο του αυτοματισμού στη διαχείριση δεδομένων και την τρισδιάστατη μοντελοποίηση των ιδιοκτησιακών μονάδων.

Η παρούσα έρευνα στοχεύει στην ανάπτυξη μεθοδολογιών και αλγορίθμων για την αυτόματη, οικονομική, ταχεία και αξιόπιστη παραγωγή 3D σημασιολογικά εμπλουτισμένων μοντέλων κτιρίων, εστιάζοντας στην περιοχή του 3D Κτηματολογίου. Η διατριβή τείνει να αξιοποιήσει τις τρέχουσες ερευνητικές τάσεις, τις καινοτόμες τεχνικές πληθοπορισμού και τα σύγχρονα τεχνολογικά επιτεύγματα, προκειμένου να αναπτύξει ένα τεχνικό εργαλείο και μεθοδολογία για την αρχική συλλογή, διαχείριση, συντήρηση, 3D μοντελοποίηση και απεικόνιση κτηματολογικών πληροφοριών και, να δημιουργήσει ένα γενικευμένο και ευέλικτο πλαίσιο, ικανό να προσαρμόζεται στη διαθέσιμη γεωχωρική υποδομή και την οικονομική κατάσταση κάθε χώρας, συμπεριλαμβανομένων ακόμη και περιοχών που δεν έχουν ακόμη 2D Κτηματολόγιο. Η διατριβή ακολουθεί και ευθυγραμμίζεται με τις παγκόσμιες προσπάθειες που στοχεύουν στην ανάπτυξη του 3D Κτηματολογίου και στη θέσπιση ενός κοινού προτύπου για τη μοντελοποίηση κτηματολογικών πληροφοριών μέσω του LADM.

Η διατριβή παρουσιάζει τις προοπτικές της χρήσης τεχνικών πληθοπορισμού για τη συλλογή 3D χωρικών και περιγραφικών δεδομένων, μέσω σύγχρονων εργαλείων και τεχνολογιών πληροφορικής, ενώ παράλληλα επιχειρεί να εισαγάγει την αυτοματοποίηση στις διαδικασίες επεξεργασίας χωρικών δεδομένων, με στόχο την παραγωγή αξιόπιστων τρισδιάστατων μοντέλων από μη ειδικούς, γρήγορα και οικονομικά. Η έρευνα ακολουθεί τρία κύρια στάδια: (i) ανασκόπηση της βιβλιογραφίας, (ii) ανάπτυξη μεθοδολογιών και τεχνικών, και (iii) πρακτική τεκμηρίωση, με υλοποίηση πρακτικών εφαρμογών. Αρχικά, διενεργείται επισκόπηση της υφιστάμενης βιβλιογραφίας σχετικά με τις πρόσφατες εξελίξεις στις τεχνικές, τις μεθόδους και τους αλγόριθμους 3D ανακατασκευής, καθώς και της χρήσης δεδομένων πληθοπορισμού στις διαδικασίες 3D ανακατασκευής κτιρίων. Στη συνέχεια, εξετάζονται οι δυνατότητες αξιοποίησης αυτών των γνώσεων για τον σχεδιασμό ενός τεχνικού πλαισίου για την υλοποίηση 3D κτηματολογικών εργασιών σε αστικές και περιαστικές περιοχές, διατηρώντας χαμηλό το κόστος των εργασιών. Τέλος, παρουσιάζονται οι αναπτυχθείσες μεθοδολογίες, τεχνικές, αλγόριθμοι και λογισμικά, συνοδευόμενα από τα κύρια συμπεράσματα, ευρήματα και προτάσεις της έρευνας.

Η διδακτορική διατριβή (ΔΔ) διαρθρώνεται σε οκτώ (8) κεφάλαια, τα οποία ανταποκρίνονται στον σκοπό της έρευνας.

Το Κεφάλαιο 1 παρέχει πληροφορίες σχετικά με το αντικείμενο της έρευνας, καθώς και τις υπάρχουσες ελλείψεις και τα κενά που στοχεύει να καλύψει η έρευνα της ΔΔ. Επιπλέον, περιγράφονται και αναλύονται οι κύριοι ερευνητικοί στόχοι και καινοτομίες της ΔΔ.

Το 2ο Κεφάλαιο εμβαθύνει στο αντικείμενο του 3D Κτηματολογίου. Μεταξύ των τριών βασικών σταδίων ανάπτυξης του, η ΔΔ εστιάζει κυρίως στο τεχνικό/τεχνολογικό τμήμα. Εξετάζει διάφορες διεθνείς προσπάθειες σχετικά με την πραγματική ή πειραματική υλοποίηση τρισδιάστατων κτηματολογικών συστημάτων και μελετά τα ευρήματα και τις προοπτικές πρόσφατων επιστημονικών συνεδρίων, ακαδημαϊκών μελετών και πιλοτικών έργων, που σχετίζονται με τα 3D Κτηματολόγια. Εν συνεχεία, παρουσιάζονται τα χαρακτηριστικά του Διεθνούς Μοντέλου Διαχείρισης Γης (LADM), δίνοντας μεγαλύτερη έμφαση στην τρισδιάστατη πτυχή του, δηλαδή στον ορισμό της γεωμετρίας και την απεικόνιση των τρισδιάστατων χωρικών οντοτήτων. Επιπλέον, επιλέγονται και παρουσιάζονται ορισμένα διεθνή προφίλ χωρών βασιζόμενα στο πρότυπο LADM. Εξετάζονται αρκετές έρευνες που προσπαθούν να συνδέσουν το διεθνές πρότυπο του LADM με ευρέως διαδεδομένα φυσικά τεχνικά μοντέλα, όπως το CityGML, IndoorGML, BIM/IFC, LandXML κ.α. Η έλλειψη σύνδεσης με κοινά αποδεκτά φυσικά μοντέλα αποτελεί ένα σημαντικό μειονέκτημα του LADM, το οποίο θα πρέπει να αντιμετωπιστεί σε μελλοντική αναβάθμιση του διεθνούς προτύπου.

Στο 3ο Κεφάλαιο παρέχεται μια ταξινόμηση των μεθόδων συλλογής 3D δεδομένων. Παρουσιάζεται η βιβλιογραφική ανασκόπηση των σύγχρονων μεθόδων, τεχνικών και αλγορίθμων 3D ανακατασκευής. Ακόμη, εξετάζεται η δυνατότητα συμβολή τους στην ανάπτυξη του 3D Κτηματολογίου. Συγκεκριμένα, πραγματοποιήθηκε κατηγοριοποίηση των υφιστάμενων μεθόδων ανακατασκευής, σε τρείς βασικές κατηγορίες: (α) Παραμετρικές μέθοδοι, (β) Μη-παραμετρικές μέθοδοι, και (γ) Υβριδικές μέθοδοι. Η επιλογή της καταλληλότερης μεθόδου ανακατασκευής εξαρτάται από πολλές παραμέτρους που σχετίζονται με την κλίμακα, τον τύπο του μελετημένου αντικειμένου ή σκηνής, τον τύπο των αρχικών δεδομένων, την απαιτούμενη ακρίβεια του τελικού προϊόντος, τη διαθέσιμη χρηματοδότηση κ.λπ., αποδεικνύοντας ότι υπάρχουν αρκετές εναλλακτικές για υλοποίηση 3D ανακατασκευών, ανάλογα με τις απαιτήσεις της εκάστοτε εφαρμογής. Τέλος, αναπτύσσονται και παρουσιάζονται δύο διαφορετικές μεθοδολογίες για την αυτόματη ανίχνευση, εξαγωγή και/ή 3D ανακατασκευή κτιρίων, και εξάγονται συμπεράσματα σχετικά με την πιθανή ένταξη τους στις διαδικασίες ανάπτυξης του 3D Κτηματολογίου. Αρχικά, παρουσιάζεται μια μεθοδολογία για τον εντοπισμό και την ανακατασκευή των οροφών κτιρίων πυκνοδομημένων αστικών περιοχών, αξιοποιώντας γεωαναφερμένα νέφη σημείων και χρησιμοποιώντας φωτογραμμετρικές τεχνικές. Στη συνέχεια, εισάγεται μια μεθοδολογία για την ανίχνευση, την εξαγωγή και διανυσματοποίηση των περιγραμμάτων των κτιρίων, από γεωαναφερμένες αεροφωτογραφίες, μέσω τεχνικών βαθιάς μηχανικής μάθησης.

Τα δεδομένα που παράγονται μέσω των αναπτυχθέντων μεθοδολογιών, είναι πολύτιμα για μια μεγάλη ποικιλία εφαρμογών, παρέχοντας ταχύτατα αξιόπιστες μετρικές πληροφορίες σχετικά με τα κτίρια που βρίσκονται στην περιοχή μελέτης. Παρόλα αυτά, ο απαιτούμενος χρόνος, το οικονομικό και υπολογιστικό κόστος αυτών, καθώς και η παραγωγή σύνθετων επιφανειών δεν ευνοεί την άμεση και οικονομικά αποδοτική ανάπτυξη του 3D Κτηματολογίου. Για τον σκοπό αυτό, η καταγραφή των 3D κτηματολογικών αντικειμένων στρέφεται σε πιο δομημένες λύσεις, όπως αναφέρθηκαν στο 2ο Κεφάλαιο, οι οποίες μπορούν να συνδεθούν άμεσα με συστήματα γεωγραφικών πληροφοριών (GIS), όπως τα κτηματολογικά συστήματα.

Το 4ο Κεφάλαιο εστιάζει στη συνεισφορά της Εθελοντικής Γεωγραφικής Πληροφορίας (VGI) και του Πληθοπορισμού, σε πραγματικές εφαρμογές 3D χαρτογράφησης του χώρου. Προκειμένου να αξιολογηθούν οι δυνατότητες των δεδομένων πληθοπορισμού στην 3D μοντελοποίηση του χώρου, και πιο συγκεκριμένα στην 3D μοντελοποίηση κτηματολογικών αντικειμένων, εξετάζονται οι υφιστάμενες προσεγγίσεις που αφορούν στην αξιοποίηση πληθοποριστικών δεδομένων σε 2D και 3D κτηματολογικές εργασίες. Συνδυάζοντας τα ευρήματα αυτών των προσεγγίσεων με τη γνώση που αποκτήθηκε από το 3ο Κεφάλαιο, αξιολογούνται οι μέθοδοι 3D ανακατασκευής και επισημαίνονται τα βασικά πλεονεκτήματα και μειονεκτήματα αυτών, κατά την αντιμετώπιση δεδομένων πληθοπορισμού, καταλήγοντας στο συμπέρασμα ότι οι παραμετρικές μέθοδοι ανακατασκευής αποτελούν τη βέλτιστη επιλογή για αυτήν την περίπτωση. Εν συνεχεία, διερευνώνται και παρατίθενται οι βασικές παράμετροι που επηρεάζουν τη συμμετοχή των πολιτών σε πληθοποριστικά έργα και την ποιότητα των πληθοποριστικών δεδομένων, με έμφαση στην ακρίβεια, ενώ συζητείται και η χρηστικότητα των εφαρμογών συλλογής δεδομένων.

Στο 5ο Κεφάλαιο περιγράφεται και παρουσιάζεται η αναπτυχθείσα μεθοδολογία για την υλοποίηση των 3D κτηματολογικών εργασιών. Η προτεινόμενη μεθοδολογία ενσωματώνει τα τρέχοντα ευρήματα, τα διδάγματα και τις τάσεις της τρέχουσας έρευνας και παρέχει ένα ευέλικτο, βιώσιμο και αποτελεσματικό μοντέλο για την αρχική υλοποίηση των 3D κτηματολογικών εργασιών μέσω τεχνικών πληθοπορισμού. Τα βασικά χαρακτηριστικά της αναπτυχθείσας μεθοδολογίας περιλαμβάνουν: (i) την ενημέρωση, την παρακίνηση και την εκπαίδευση των συμμετεχόντων/ιδιοκτητών, (ii) τη χρήση σύγχρονων εργαλείων πληροφορικής, με έμφαση στις κινητές υπηρεσίες/συσκευές, (iii) την καθιέρωση ενεργούς συνεργασίας μεταξύ των συμμετεχόντων/ιδιοκτητών και επαγγελματιών μηχανικών, και (iv) την ενσωμάτωση καινοτόμων τεχνικών στις διαδικασίες συλλογής δεδομένων και 3D μοντελοποίησης. Επιπλέον, προσδιορίζονται οι πιθανοί εναλλακτικοί τύποι γεωχωρικών δεδομένων που μπορούν να ενσωματωθούν στο αναπτυχθέν μεθοδολογικό πλαίσιο. Εκτός από τα κοινώς χρησιμοποιούμενα υπόβαθρα καταγραφής (π.χ. ορθοφωτογραφίες, κτηματολογικοί χάρτες, αρχιτεκτονικές κατόψεις κ.λπ.), προτείνεται η ενσωμάτωση φυσικών/τεχνικών μοντέλων, κυρίως από εφαρμογή BIM, αλλά και καινοτόμων τεχνικών μηχανικής μάθησης για την υλοποίηση κτηματολογικών εργασιών σε εσωτερικούς χώρους. Σε αυτό το Κεφάλαιο, παρουσιάζεται επίσης ένα παράδειγμα υιοθέτησης του αναπτυχθέντος μεθοδολογικού πλαισίου στην ελληνική πραγματικότητα.

Στο 6ο Κεφάλαιο περιγράφεται και παρουσιάζεται η αρχιτεκτονική του αναπτυχθέντος τεχνικού συστήματος, που σκοπεύει να υποστηρίξει την προτεινόμενη μεθοδολογία. Τα κύρια τμήματά του αποτελούνται από: (α) την πλευρά του διακομιστή και (β) την πλευρά του πελάτη/χρήστη. Για την πλευρά του διακομιστή, αναπτύχθηκε ένα σχήμα βάσης δεδομένων βασιζόμενο στις προδιαγραφές του LADM, ικανό να δομεί και να διαχειρίζεται διαφορετικούς τύπους δεδομένων εντός της ίδιας πλατφόρμας. Για την πλευρά του πελάτη/χρήστη αναπτύχθηκε και παρουσιάζεται μια εφαρμογή για κινητές συσκευές και μια διαδικτυακή εφαρμογή, με πολλαπλές και διαφορετικές λειτουργίες. Οι αναπτυχθείσες κτηματολογικές εφαρμογές στοχεύουν να βοηθήσουν στην υλοποίηση 3D κτηματολογικών εργασιών, επιτρέποντας την συμμετοχή μη επαγγελματιών στη διαδικασία κτηματογράφησης και 3D μοντελοποίησης των κτηματολογικών αντικειμένων. Σημειώνεται ότι το πρωταρχικό ενδιαφέρον της παρούσας έρευνας εστιάζεται στη γεωμετρία και την αναπαράσταση των φυσικών τρισδιάστατων κτηματολογικών αντικειμένων (χωρικές οντότητες), ενώ η λεπτομερής μελέτη των νομικών θεμάτων δεν εμπίπτει στους στόχους της.

Στο 7ο Κεφάλαιο το αναπτυχθέν τεχνικό πλαίσιο υλοποίησης 3D κτηματολογικών εργασιών, ελέγχεται σε πρακτικό επίπεδο. Στο πλαίσιο της διδακτορικής διατριβής υλοποιήθηκαν δέκα (10) πρακτικές εφαρμογές, ακολουθώντας το προτεινόμενο μεθοδολογικό πλαίσιο και αξιοποιώντας διαφορετικούς τύπους υποβάθρου καταγραφής. Οι τύποι υποβάθρου καταγραφής που εξετάστηκαν, ανήκουν σε τρείς ευρείες κατηγορίες ανάλογα με τη δισδιάστατη ή τρισδιάστατη μορφή τους: (α) χαρτογραφικά υπόβαθρα και (β) δεδομένα BIM. Πέρα από την εξέταση των επιμέρους κατηγοριών, εξετάζεται και η ταυτόχρονη αξιοποίηση των δύο κατηγοριών. Οι πρακτικές εφαρμογές διερευνούν τόσο την χρήση των κινητών υπηρεσιών όσο και των διαδικτυακών εφαρμογών, δίνοντας μεγαλύτερη έμφαση στη χρήση των κινητών υπηρεσιών και συγκεκριμένα στην αξιοποίηση εφαρμογών για κινητές συσκευές. Οι περιοχές μελέτης αφορούν κυρίως πυκνοκατοικημένες αστικές περιοχές, αλλά και περιοχές με αραιή δόμηση. Με βάση τα αποτελέσματα των πρακτικών εφαρμογών και τις απόψεις των συμμετεχόντων, εξήχθησαν και παρατίθενται ορισμένα βασικά συμπεράσματα σχετικά με τις προοπτικές, την αποτελεσματικότητα, τη χρησιμότητα, την αξιοπιστία και την ποιότητα του αναπτυχθέντος τεχνικού πλαισίου.

Τέλος, το 8ο Κεφάλαιο παρέχει τα συνολικά συμπεράσματα της ΔΔ, παραθέτοντας τα κύρια ευρήματα των προηγούμενων Κεφαλαίων, του αναπτυχθέντος τεχνικού πλαισίου υλοποίησης 3D κτηματολογικών εργασιών μέσω τεχνικών πληθοπορισμού; και της ποιότητας των πληθοποριστικών δεδομένων. Επίσης, περιλαμβάνονται περαιτέρω σκέψεις και ιδέες για μελλοντική έρευνα.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
4D	Four-Dimensional
AAA	Accurate, Assured and Authoritative
ADE	Application Domain Extensions
ALS	Aerial Laser Scanner
BA	Boundary-Aware
BCE	Binary Cross Entropy
BIM	Building Information Model
BL	Boundary Loss
BR-Net	Boundary Regulated Network
CAD	Computer Aided Design
CDP	Coherent Drift Point
CGA	Computer Generated Architecture
CNN	Convolutional Neural Networks
CV	Computer Vision
DBMS	Database Management Systems
DEM	Digital Elevation Model
DoG	Difference of Gaussians
DoN	Difference of Normals
DT	Digital Twins
DTM	Digital Terrain Model
DSM	Digital Surface Model
DXF	Drawing eXchange Format
EA	Enterprise Architect
ESRI	Environmental Systems Research Institute
EU	European
Exif	Exchangeable Image File
FAO	Food and Agricultural Organization of United Nation
FCN	Fully Convolutional Networks

FFP	Fit-For-Purpose
FIG	Federation of Surveyors
GB	Grammar Building
GCRS	Geographic Coordinate Reference System
GDAL	Geospatial Data Abstraction Library
GGIN	Global Geospatial Information Management
GGRS87	Greek Geodetic Reference System 1987
GIS	Geographic Information System
GML	Geography Markup Language
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HC	Hellenic Cadastre
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IFC	Industry Foundation Classes
IMU	Inertial Measurement Unit
INSAR	Interferometric Synthetic Aperture Radar
INSIRE	Infrastructure for Spatial Information in Europe
IoU	Intersection of Union
IPS	Indoor Positioning System
ISO	International Organization for Standardization
IT	Information Technology
KML	Keyhole Markup Language
LADM	Land Administration Domain Model
LAS	Land Administration Systems
LIDAR	LIght Detection and Ranging
LOD	Levels of Detail
LSD	Line Segment Detector
Lsystems	Lindenmayer-systems
MC-FCN	Multi-Constrained Fully Convolutional Network
MDA	Model Driven Architecture
MLAS	Multipurpose Land Administration System

MLS	Moving least square
m-services	mobile services
MSM	Minimum Square Method
MVS	Multi View Stereo
NCMA	National Cadastral Mapping Agency
NDCB	National Digital Cadastral Data Base
nDSM	normalized DSM
NDVI	Normalized Difference Vegetation Index
NMA	National Mapping Agency
NTUA	National Technical University of Athens
OBB	Oriented Bounding Box
OBM	OpenBuildingModels
OMG	Object Management Group
OSM	Open Street Maps
OSS	Open Source Software
PCA	Principal Component Analysis
PCD	Point Cloud Data
PCRS	Projected Coordinate Reference System
PMVS	Patch-based Multi View Stereo
POI	Point of Interest
RANSAC	Random Sample Consensus
RBF	Radial Basis Function
RGB	Red-Green-Blue
RMSE	Root Mean Square Error
ROI	Region Of Interest
RRRs	Rights Restrictions Responsibilities
SAR	Synthetic Aperture Radar
SDGs	Sustainable Development Goals
SGM	Semi-Global Matching
SFM	Structure-From-Motion
shp	shapefile
SOR	Statistical Outlier Removal

SQL	Structured Query Language
SRPO	Special Real Property Objects
SRSG	School of Rural, Surveying and Geoinformatics Engineering
SRTM	Shuttle Radar Topography Mission
SVM	Support Vector Machine
TLS	Terrestrial Laser Scanners
UAV	Unmanned Aerial Vehicle
UML	Unified Modelling Language
UN	United Nation
UN-Habitat	United Nation Habitat
VGI	Volunteer Geographic Information
WGS84	World Geodetic System 1984
WHO	World Health Organization
WiFi	Wireless Fidelity
XML	eXtensible Markup Language

Chapter 1
Introduction

1.1 Background

During the last centuries, population density has increased considerably making land use and urban densities more intense with an ever-increasing prevalence of multidimensional infrastructures in the urban environments. The World Health Organization (WHO) reported that in 2014 that 54% of the world's people lived in urban areas, up from 34% in 1960. The tipping point, according to most authorities, occurred in 2007, when there were more urban dwellers than rural residents in the world: the so-called "urban millennium". The United Nations predict that by 2050, 66% of the world's population will live in urban areas. Much is being written about the growth of urban populations and the concurrent growth of urban geospatial infrastructures and institutions to support this huge growth of two-thirds of the world's population. Experts all over the world are working toward the same goal: trying to increase the "value" of geospatial data and urban geospatial infrastructures for the society in order to achieve more benefit, more transparency, more safety, more environmental quality, more growth, more fairness, more efficiency in governance of urban areas and more smart cities.

Smart cities are mapped in various levels of detail and are appropriately designed in order to optimize their resources, maintain sustainability and improve peoples' life quality. Having reliable and updated 3D model of the built environment empowers these perspectives, providing also a valuable input for many applications such as urban planning, land administration, 3D cadastre, digital twins, security applications against natural and manmade disasters, navigation, climate crisis and risks management. 3D reconstruction is a well-studied problem both in photogrammetry and computer vision, occupying the research community for more than thirty years. Traditional photogrammetric mapping has been in the realm of industrial organizations collecting aerial imagery, developing maps and generate 3D information of urban spaces (Leberl, 2010). In recent years, the field of 3D reconstruction has gained a lot of attention due to the rapid evolution of technology and the development of new digital capturing methods and systems. Photogrammetric and computer vision tools as well as depth and consumer-grade cameras enable an intuitive and cost-efficient way of capturing 3D scenes as point clouds. However, for several applications a point cloud does not consists a sufficient data source and therefore the acquisition of other 3D information is required, in order to obtain a polygonal representation.

The large variety of applications produces different requirements on reconstruction systems. The applications should be oriented according to the development field that are referred to, and the purpose they serve. For some applications the accuracy of the final product is of a great importance. Other applications might tolerate approximations but their main objective is to create spatially reliable integrated models. In the latter, the reconstruction techniques should be easy-to-use in order to be wieldy for non-experts. This means, that the 3D modeling algorithms should be either fully automatic or have a simple and accessible user interface. While it is not always necessary to have an exact transcript of a real scene, reconstructions can provide a variety of information regarding the style, the geometry, the underlying structuring elements of buildings or cities, or even include descriptive information concerning immovable and proprietary background. This information can be used for automatically generating new virtual worlds with procedural modeling techniques, enriched with descriptive elements useful in several application fields.

Of all the institutions that must be developed to anticipate, keep abreast of and support this growth, the cadastre stands foremost in the interest of commerce, real estate investment, municipal revenue, and personal property security, not to mention urban planning and management. Geo-information professionals and cadastral experts all around the world are working together to develop services to deliver administrative, economic and social benefits, as well as fit-for-purpose land administration solutions and land policies for sustainable urban management.

Today, private property rights are recognized as a fundamental element of modern market economies. The recognition of the importance of private property rights has led in turn to the need for their registration in order to provide secure ownership of land and to support the operations of the property market and global economic development. As less than 30% of land has been registered in cadastral systems, land surveyors today focus their services on the purpose of a global registration of property rights and aim to provide a functional solution, reliably and affordably, for a complex and rapidly changing world that has adopted the 2030 UN Global Sustainable Development Agenda to address global challenges, among them, to eliminate poverty by 2030, so that no one will be left behind. The Sustainable Development Agenda 2030 target 1.4. recognizes that "by 2030, countries should ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance." (General Assembly Resolution 70/1 2015). As shown by Dawidowicz and Zrobek (2017) the achievement of SDG targets 1,2,5 and 11 is directly linked to LASs, as the fulfilment of the former requires the existence of the latter. In this effort, it has been recognized that traditional 2D cadastral surveys (of land parcels, property rights and responsibilities) are expensive and time-consuming. Therefore, research has been directed towards introducing modern, low-cost geospatial and cadastral data capturing methods, if possible using crowdsourcing methodology and mobile services, which will enable greater citizen participation in order to speed up the compilation of the cadastral surveying of the world's remaining unregistered 70% of land and reduce costs (Keenja et al., 2012; Basiouka and Potsiou, 2012a,b; Basiouka and Potsiou, 2013; Basiouka et al., 2015; Enemark et al., 2014, 2015; Mourafetis et al., 2015; Apostolopoulos et al., 2015; Gkeli et al., 2016).

However, cities growth both vertically and horizontally, demanding the spatial determination and management of the third dimension. No reality has a more direct bearing on the subject of 3 dimensional geoinformation and 3D cadastre than the growth of large cities, especially in the developing countries of the world, and in the phenomenon of mega cities. It is recognized that the current cadastral systems, based on two-dimensional cadastral maps, may not be efficient enough to visualize the exact boundaries of the 3D property units to which property rights may refer in complex urban areas in the near future, and therefore may not be reliable for supporting urban activities (Rautenbacha et al., 2016; Rautenbacha et al., 2015a). The sustainable management of large and mega cities requires transparency and credibility in the determination of property rights at every level, bringing the 3D cadastre into the spotlight. 3D cadastre has been attracting researchers throughout the world for nearly a decade, bringing in line very interesting approaches regarding the development of 3D Cadastres and describing how 2D cadastral systems should best be transformed into 3D cadastres.

With the introduction of the Land Administration Domain Model (LADM ISO 19152, 2012) in 2012, a formal mechanism is provided for the description of both 2D and 3D cadastral data. The LADM is a key tool for the appliance of harmonization, standardization and exchangeability of data, which are significant values for the effective management of the various types of rights. Actors such as United Nation Habitat (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). Although LADM offers several representations for 2D and 3D cadastral data the definition of the acceptable 3D cadastral object representations and the corresponding 3D geometries are still under investigation. Some researchers have investigated the potential use of existing 3D data and LADM standard trying to link 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).

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

Keeping in mind that the need for a fit-for-purpose technical procedure for establishing a 2D cadastral system is urgent in the developing countries of the world today, there is a similar need for a fit-for-purpose procedure for a 3D cadastral system in the mega cities of the developing world as well. Thus, developing inclusive solutions for the compilation of fit-for-purpose 3D cadastres reliably, affordably and in a timely manner, is paramount, in order to satisfy the future urban needs and to support the SDGs for 2030, in both developed and less developed areas, wherever there may be the necessary political will to recognize, legally empower and register private property rights.

1.2 Research Objectives

While in the past the reconstruction processes were overshadowed from laborious and time-consuming processes, the introduction of automation shakes off those barriers, signifying a new era for 3D reconstruction. The rapid development of computer vision technology and techniques, contribute significantly to the automation of the reconstruction process, reducing the required time, costs and human resources, while the tremendous increase in the availability of low-cost computer resources, makes the 3D reconstruction more accessible and applicable in several areas. At the same time, the exploitation of data from unstructured sources, such as images from consumer-grade cameras and crowdsourced data, and their combination with data from structured sources, create a new application-oriented environment, with different requirements on 3D modeling techniques and systems, depending on the purpose of their development. The automatic generation of 3D building models and the creation of a constantly updated 3D Geographic Information System (GIS) of the real environment, including urban, suburban and rural areas, is an important geospatial tool of the modern world, that creates valuable 3D geospatial content for various purposes, such as 3D cadastres.

In this context and in the light of the aforementioned research background, the overall aim of this doctoral dissertation is the development of methodologies and algorithms of photogrammetry and computer vision, for the automatic, affordable, fast and reliable generation of 3D semantically-enriched building models, focusing on the area of 3D Cadastres, the implementation of which is required at European level. This effort aims to harmonically integrate the current research trends, innovative methods and technologies in order to develop a technical tool and a methodology for the initial data acquisition, management, maintenance, 3D modeling and visualization of cadastral units, and establish a more generalized framework that is adjustable to the available geospatial infrastructure and financial situation of each country, including even regions that still lack registration of 2D cadastral data.

This doctoral dissertation does not focus on exploring the optimal 3D geometric representation and visualization of all existing types of legal rights. Instead, it primarily focuses on the technical background concerning the 3D representation of the spatial extent of the property units’ legal space at LoD1.

While the practical experiments were conducted in the Greek area, drawing on the experience of Greece and the Greek cadastre, the dissertation's objective is not to offer a specific proposal solely for Greece. Instead, it aims to provide a generalized model that can be adapted by countries with diverse cartographic and legal backgrounds. However, it is possible to modify and enrich the proposed framework to create a 3D cadastral system in Greece as well.

Hence, the main research objectives that stem from the overall aim of this dissertation are:

- the establishment of automatic workflows for the detection, extraction and reconstruction of buildings based on photogrammetric and computer vision techniques;
- the establishment of an automatic cost-effective workflow for 3D buildings modeling based on the combined exploitation of photogrammetric, computer vision and crowdsourcing techniques;
- the introduction of crowdsourcing techniques, automation and mobile services (m-services) in 3D cadastral surveys, reducing the costs, the compilation time and simplifying the 3D cadastral surveys including the acquisition of the initial 2D/3D cadastral information and the modeling procedure;
- the establishment of an alternative crowdsourced model for 3D cadastral surveys with the least possible requirements in data, time and human resources;

- the establishment of an active cooperation between citizens/rights holders and professionals in the cadastral procedures and reconsideration of the role and the responsibilities of the latter ones in the whole process;
- the investigation of: (i) the alternative data sources that may be adapted in 3D cadastral procedures, and (ii) the potential contribution of photogrammetric and machine learning techniques in providing fast and reliable 2D and 3D information for 3D cadastral procedures;
- the adoption of the international standard of LADM for structuring the crowdsourced cadastral data;
- the establishment of a cost-effective and reliable technical geospatial tool able to support 3D Cadastres and provide valuable information for a variety of other applications, such as digital twins, smart cities, and set the basis for the development of Four-Dimensional (4D) systems, such as 4D cadastres.

1.3 Contribution and Originality

The overall contribution of this dissertation lies in establishing an affordable and flexible practical technical solution for the initial implementation of 3D crowdsourced cadastral surveys, exploiting the available geospatial infrastructure of each country and including regions that still lack registration of 2D cadastral data. The main contributions of the research, are the following:

- *The introduction of crowdsourcing in 3D cadastral surveys.* Until now, crowdsourcing has been used for mapping purposes and has been successfully introduced in 2D cadastral surveys. In this doctoral dissertation, crowdsourcing techniques are linked to 3D cadastral procedures and therefore to 3D modeling of the cadastral objects.

- *The introduction of automation in 3D modelling of crowdsourced cadastral objects.* 3D modelling of the real environment consists a well-studied problem in the field of photogrammetry and computer vision, with many techniques and methods that lead to the partial or full reconstruction of complex scenes or man-made objects. At the same time, the field of 3D cadastre is newly emerging, trying to synthesize the physical and legal counterparts of the cadastral objects and connect them with cadastral semantic information. So far, various approaches concerning the modelling and visualization of the cadastral objects have been proposed, focusing mainly on time-consuming and expensive procedures using common application schemes and technical models. In this study a cost-effective parametric modelling method is established for the automatic, fast and reliable 3D modelling of the crowdsourced cadastral objects. The introduction of automation in 3D cadastral modeling enables non-experts to generate reliable 3D models of property units and provide a clear view of the spatial extent of the vertically stratified cadastral objects and the Rights Restrictions Responsibilities (RRRs), in a short time frame.

- *The establishment of a new crowdsourced model for 3D cadastral surveys and a technical practical tool for the acquisition, management, modeling, storage, maintainance and visualization of 3D cadastral objects.* The research synthesizes various investigations from international crowdsourced cadastral mapping projects, 3D Cadastres practices, LADM specifications and current technological trends, and designs a flexible model and technical background as basis for the fast, affordable and reliable implementation of 3D cadastral surveys.

- *The establishment of a two-way model of cooperation between volunteers, citizens, technicians, inspectors and professionals.* Citizens' participation in cadastral procedures is quite limited in most countries, resulting in gross errors and time delays in the completion of the cadastral registration procedures. The recruitment of the rights holders, who know better the boundaries and location of their properties, and the establishment of a mutual relationship with experts and professionals, increase the reliability of the cadastral surveys by eliminating the gross errors and the obstacles that prevent the completion of the cadastral process.

- *The introduction of new alternative data sources and technologies to support the 3D cadastral procedures in cases of weak registration background availability.* This research investigates and proposes: (i) the integration of machine learning techniques for the generation of location data, through the combined use of Bluetooth sensors and mobile devices; the establishment of an Indoor Positioning System (IPS) enables the identification and delimitation of the geometry of the buildings properties units/condominiums, in cases where the architectural floor plans are not available; and (ii) deep learning techniques for the production of a vector buildings basemap, to assist the cadastral recording process.

1.4 Structure of the Dissertation

Chapter 1 briefly describes the current research background identifying the wide application range of 3D models and the open research issues related to 3D cadastres that triggered the implementation of this research. Then, the overall aim and the research objectives of this doctoral dissertation and its contribution and originality are outlined. Finally, an overview of the content and structure of this dissertation is presented.

Chapter 2 provides a literature review of international efforts that attempt to implement real or experimental 3D cadastral systems. Next, the main features of the international standard of LADM are presented, emphasizing on its 3D aspect. Subsequently, the structure of various international paradigms of country-level LADM-based profiles is examined; while then recent researches trying to set a link between LADM and commonly used technical data models (such as CityGML, IndoorGML, BIM / IFC, LandXML), are presented. Finally, the main conclusions concerning this Chapter are drawn.

Chapter 3 provides a comprehensive overview of 3D reconstruction algorithms and techniques that generate 3D models from different data sources. The main focus is on man-made scenes, namely buildings. First, a classification of the different 3D data acquisition methods and the most common 3D input data required by the majority of reconstruction methods, is presented. Then, an extensive literature review of the state-of-the-art 3D reconstruction methods, techniques and algorithms, concerning the 3D reconstruction of buildings, is made. Following, the research focuses on the exploitation of high-resolution geo-referenced aerial imagery. Two discrete methodologies are developed for the detection, extraction and potential reconstruction of buildings sparsely or in densely urbanized areas, respectively. The main stages of the developed methodologies and software are described. Then, the produced data are assessed and the main conclusions are presented. Finally, the potentials of the developed methods in 3D cadastral processes is discussed and the main conclusions of this Chapter are introduced.

Chapter 4 presents some international research initiatives related to 3D modelling utilizing 3D data collected mainly through VGI and crowdsourcing techniques. Then, a literature review concerning the current crowdsourced approaches for the implementation of 2D cadastral surveys is presented; while the potentials of the crowdsourced data in 3D cadastral modeling are assessed. Subsequently, the main parameters influencing the recruitment of citizens in a crowdsourcing project; the quality of the crowdsourced data; and, the usability of the data capturing tool, are presented.

Chapter 5 presents the developed crowdsourced methodology for the initial implementation of 3D cadastral surveys. The main leading principles followed for the development of the methodological framework; as well as the reasoning for choosing mobile devices as the main data capturing tool, are described in detail. Then, the main phases of the developed crowdsourced cadastral workflow are described and illustrated; while a Greek paradigm trying to adopt the crowdsourced workflow in the Greek reality, is presented. Finally, the main conclusions concerning the potentials of the developed, are presented.

Chapter 6 provides a comprehensive overview of the architecture of the developed technical system; the detailed description of the sub-systems; and, how all the included parts work together in synergy. First, the developed prototype mobile application for 3D cadastral data acquisition, 3D parametric modelling and visualization of real properties is presented; while the developed web application for viewing and manipulating the available BIM data as well as for collecting, storing and updating the 3D cadastral data regarding the properties RRRs and the right holders is presented. In this dissertation, the utilization of a mobile application as the main data capturing is predominated, however with the development of the web application an alternative solution is also investigated. Each of the development stages, software tools and functionalities of both applications are described in detail. Following, a LADM-based database schema is developed aiming to be the repository of the collected 3D crowdsourced data and facilitate their further management, storage and maintenance. The main objective of this venture is to provide an integrated solution able to structure and manage different data types into the same platform. Finally, the main conclusions regarding the developed technical system are presented. It should be noted that the main objective of this thesis 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.

Chapter 7 provide a practical documentation of the developed 3D crowdsourced cadastral framework. First, the necessary pre-processing steps applied to the different types of the supported geospatial background in order to be exploited by the cadastral applications, are presented. Moreover, the practical implementations utilizing: (i) the developed application for mobile devices, and then, (ii) the developed web application, are presented and evaluated. A total of ten practical experiments are implemented in urban and suburban areas of Greece. The case studies follow different methodological steps, related to the current available registration background and the development stage of the cadastral mobile or web application. Different types of registration basemaps including cartographic basemaps, BIM data or their combination are examined. The proposed crowdsourced methodological approach is followed in all experiments, starting with informing participants about the purpose and benefits of the process; their training on geometry matters and the function of the mobile/web application; data collection with the active and ongoing support from the team leaders; the completion of fieldwork and the collection of participants' views concerning the overall process; and, the export and control of 3D crowdsourced results. Finally, the main conclusion concerning the perspectives, effectiveness, usability, reliability and quality of the developed technical framework are realized.

Finally, in Chapter 8, a summary and the contribution highlights of this dissertation; the main conclusions derived for the developed 3D crowdsourced technical framework and the data quality; and, some further thoughts and ideas for future research, are outlined.

Chapter 2

Three Dimensional (3D) Land Administration Systems

Through the ongoing rapid urbanization, several complex constructions with multi-dimensional and overlapping property rights have emerged. The growing dominance of multi-dimensional infrastructures in the urban environment increases the complexity in land administration procedures introducing new challenges in recording, managing and visualising the spatial extent of vertically stratified cadastral objects. Traditional 2D cadastral systems are challenged to handle recording, managing and visualizing the spatial extent of the vertically stratified cadastral objects. 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, the reduction of risks, time and costs in land and property transactions and mortgages, the improvement of land use and management of urban areas, the reduction of poverty and the safeguarding of ownership in the highly urbanized world.

The first international discussion regarding the 3D cadastre took place in 2001 at the workshop entitled 3D Cadastres, under the seventh commission of the International Federation of Surveyors (FIG). In April 2010, at the 24th FIG congress held in Sydney, the reestablishment of a working group named '3D Cadastre' was decided, aiming to promote the research on 3D cadastre topic. The main objective of this working group is to create a functioning structure for 3D cadastre, determining both its main concept and terminology as well as the common levels for 3D cadastre applications. The main concept and terminology were defined by adopting the international standard of the LADM (ISO 19152) (ISO, 2012), while three main levels of 3D cadastral application were defined, namely legal, organisational and technical (Döner, 2021). Through the adoption of the LADM standard, the harmonization, standardization and exchangeability of data are achieved, which are values of great importance for the effective management 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 FIG support and emphasize the existence of these principles (Lemmen et al, 2015).

In recent decades, 3D cadasters have been a major topic of interest as they present the spatial extent of ownership and designate the 3D property RRRs. However, the implementation of a fully functional 3D cadastre has not been achieved yet (Koeva et al., 2019). In order to realize a 3D cadaster, three main stages of development should be considered: (i) the legal stage (ii) the institutional stage, and (iii) the technical stage (Lemmen & Oosterom, 2003). The legal stage consists one of the most important phases for the implementation of 3D cadasters, as without the laws and the legal definition of 3D properties, the cadastral surveys and the registration of 3D objects and rights are meaningless (Kitsakis & Dimopoulou, 2014). Subsequently, the institutional stage includes the authority and the duties of the public registration and mapping institutions for 3D registration (van Oosterom, 2013). It describes what information is needed for registration and how this information will be structured, registered, stored, and presented. It is responsible for the management, update, and distribution of the 3D cadastral data as well as the required workflow for the implementation of the 3D cadastre. Finally, the technical stage concerns how the 3D spatial information of the property units is integrated with the existing cadastres (Guo et al., 2013). To date, the main research interest in the technical stage has focused on spatial data infrastructures, Geographic Information Systems (GISs), the LADM, database management systems, 3D visualization, and 3D geometric representation, topology, and data exchange formats.

In the past twenty years, several scientific meetings, academic studies, and pilot projects have been performed on 3D cadastre. Nevertheless, during that period, there have been also significant technological achievements and changes in the visualization of 3D data, data collection techniques, the usability of various application schemas and technical models (such as CityGML, IndoorGML, BIM/IFC, LandXML, InfraGML, etc.), as well as in policies and institutional structures. The introduction of LADM and its utilization for the development of the 3D cadastre brought to the fore several interesting approaches trying to exploit the abovementioned technical models with LADM. Such rich data models are nowadays utilized in several application areas with great efficiency and have become a valuable data source for Geographic Information Systems (GIS) such as 3D cadastral systems. This has resulted in the development of various approaches to modeling the 3D information on individual units utilizing the GML-based (Geography Markup Language) (CityGML, IndoorGML) and IFC-based (Industry Foundation Model) (BIM) spatial data models. In addition, other studies on 3D cadasters are being supported in projects under the subheadings of 'Smart Cities' and 'Digital Twins' within the scope of the European Union Horizon 2020 grant program. The main objective of these studies is to provide an infrastructure enabling the design, management, and planning of sustainable cities by integrating 3D digital cadastral information with other data, such as data on energy, air pollution, mobility, and temperature (Stoter et al., 2019).

Obviously, there are several different alternative data structures that may be exploited to describe 3D cadastral objects. Among them, the Building Information Model (BIM) is indisputably one of the most comprehensive and intelligent 3D digital approaches able to manage buildings with composite structures and enable communication between stakeholders with different backgrounds (Atazadeh et al., 2019). BIMs represent the geometry of the complex physical buildings' spaces (rooms, corridors, walls, and floors) and can be modeled, managed, and maintained hierarchically in BuildingSMART open exchange standards, such as the IFC standard, enabling communication and the exchange of building information through different platforms. The integration of the BIM/IFC and the LADM standard may provide a valuable input to the 3D cadaster for each individual property as well as its surrounding properties, allowing the capture of a clearer picture regarding properties' RRRs. This view is strengthened by the fact that, nowadays, the main source of 3D building information on new buildings is BIMs. Therefore, a number of BIMs are available and can be used as an accurate basis for the collection of the needed 3D cadastral information. By laying the appropriate foundations today, BIMs may be the basis for the development of 3D cadasters in future urban centers, as they can include a wealth of useful information, such as land/property uses, property values, and energy classes.

The transformation between the conceptual and the technical model is of great importance. The Unified Modelling Language (UML) and the Object Constraint Language (OCL) has been defined from the Object Management Group (OMG) (Oriol & Teniente, 2014) in order to determine the conceptual schemas as well as to model and design the constraints of the information systems. Such standardized model may be implemented through Geographical Information Systems (GIS) and database technology, supporting data maintenance activities and the provision of elements of the model. The most-known tools capable of utilizing such an automated conversion are the SWISS standard of INTERLIS language and the Enterprise Architect UML modeling tool from Sparx Systems.

In this Section, several interesting international efforts concerning actual or experimental implementation of a 3D cadastral system, are examined. The main characteristics of LADM, together with the results of the recent research referring to the 3D aspect of LADM, are presented. International paradigms of country-level LADM-based profiles for various countries, as well as several investigations trying to implement a connection between LADM and technical data models (such as CityGML, IndoorGML, BIM/IFC, LandXML) are selected and listed. Finally, the main conclusion regarding this Chapter is presented.

2.1 International experience

The third dimension in cadastre mainly facilitates subdivision of buildings into strata, creating separate property units above or below the original ground surface. The typical types of such property units are apartments or buildings registered as private properties, either separately from the land parcel they are built on, or related to the land parcel since the rights holders of those units may also be rights holders of shared ownership rights on the parcel as well as on the common areas of the building. Other facilities such as tunnels and underground construction such as transportation or utility networks, and privately owned underground commercial or public spaces, may also be registered in a 3D cadastre, or in a different register as separate property units. This dissertation mainly focuses on the registration process of 3D property units, including the rights and responsibilities attached to those units, as in multi-story, multi-unit buildings (whether or not held apart from the land parcel), and the individual parts/subdivisions of those buildings such as condominiums (however dimensionally arranged). Such buildings usually have two components: the privately owned units and the jointly owned (common) sections of the buildings.

Many countries have developed clear legal procedures for the establishment and registration of rights of 3D property units in their cadastres. Moreover, during the last decade, many are considering interesting approaches to visualization of such data, and how their 2D cadastral systems may best be transformed into 3D cadastres that will include a 3D graphical representation of the property units and the rights associated with them. However, the most difficult phase in terms of costs and time demand is still the initial 3D cadastral data capture. Some examples of the progress achieved in this effort are given below.

One of the first countries to envision a 3D cadastre was Australia. Since the 1960s, freehold titles for 3D cadastral objects have been guided by the Land Title Act 1994. In 1997, 3D geometry could be represented as volumetric parcels in the cadastral system of Queensland (Stoter & Oosterom, 2005). 3D parcels have been accommodated in the Queensland cadastre via building parcels, restricted parcels, volumetric parcels and remainder parcels (Karki, 2013). Despite developments legally, three-dimensional property information is included in the descriptive database without being accompanied by a three-dimensional representation. 3D properties appear as 2D on the cadastral map, accompanied by their titles and the three-dimensional information defined according to the regulations (strata titles). In Queensland, plans with 3D objects are volumetric plans, whereas in other states they are called stratum plans. All possible rights, restrictions and responsibilities that can be registered in 2D can also be registered as 3D parcels. Currently, Queensland is investing in the development of the 3D QLD initiative, aiming to provide 3D indoor navigation and 3D augmented reality through the cadastral database (QLD3D, 2022).

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

Victoria is another Australian jurisdiction that strongly supports the development of 3D Cadastre. However, the depiction of the 3D RRRs is still not operational, similarly to Queensland (Kitsakis el., 2018). Despite that, the Land Use Victoria in cooperation with the University of Melbourne has created a prototype 3D digital cadastral system for Victoria (Shojaei et. al., 2016). Research on a 3D digital cadastre's technical feature is currently being conducted (Shojaei et al., 2016). Based on the roadmap that has been created, the Victorian 3D digital cadastre will be implemented by 2025 (CSDILA, 2019).

Another interesting example is the 3D Cadastre approach of Shenzhen, in China. Rapid urbanization has led to the development of mega cities in China with especially complex urban infrastructures. The traditional 2D cadastre could not manage the ever-expanding 3D urban planning and land use processes. The Property Law of 2007 opened the way for the development of a 3D cadastre and registration system, and in 2012, a 3D cadastral management prototype was created in Shenzhen (Guo et al., 2014). This prototype includes the geometry of 3D property objects and compatible 3D data models, and generates 3D model data and 3D topologies. The primary method for acquiring 3D data is to extrapolate the spatial extent of 3D features from already-existing 2D blueprints (Guo et al., 2011). Although there is significant progress, the amendment of the relevant laws and regulations is essential in order to support the complete 3D data organization.

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

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

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

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

2.2 The Land Administration Domain Model

The Land Administration Domain Model (LADM) (ISO-TC211 2012) (ISO, 2012) is maintained by ISO/TC211 and consists one of the first spatial domain standards, providing a flexible conceptual schema as basis for the development of 2D and 3D cadastres based on a Model Driven Architecture (MDA). It focuses on the rights, responsibilities and restrictions affecting land (or water), and therefore their geometrical/geospatial components. Domain standardisation is required in order to capture the semantics of the current form of land administration based on the basic agreed standards for geometry, temporal aspects, metadata and also observations and measurements from the field (Lemmen et al., 2015). LADM is already in use as conceptual model for the development of country profiles; it is integrated in the data specification of cadastral parcels in INSPIRE (INSPIRE, 2009) and the Land Parcel Identification System of the European Union (ISO, 2012); and, it is utilized as basis for software development initiatives at FAO (FAO, 2011) and UN Habitat (Lemmen, 2010), etc.

LADM establishes a shared ontology, enabling the communication between the involved parties within one country or between different countries, and facilitates the data exchange in heterogeneous and distributed land administration environments. The fundamental elements distinguishing LADM's design, are originated from the common aspects encountered in global land administration systems, which are the legal/administrative data, party/person/organisation data, spatial unit (parcel) data, data on surveying or object identification and geometric/topological data (Lemmen et al., 2015). Hence, LADM conceptual schema consists of three main packages, namely the Party package (green), the Administrative package (yellow) and the Spatial Unit package (blue) with its sub package Representation and Survey (red), forming the core elements of a multipurpose land administration system (MLAS). These classes are presented through the Unified Modelling Language (UML) class diagram in Figure 1.

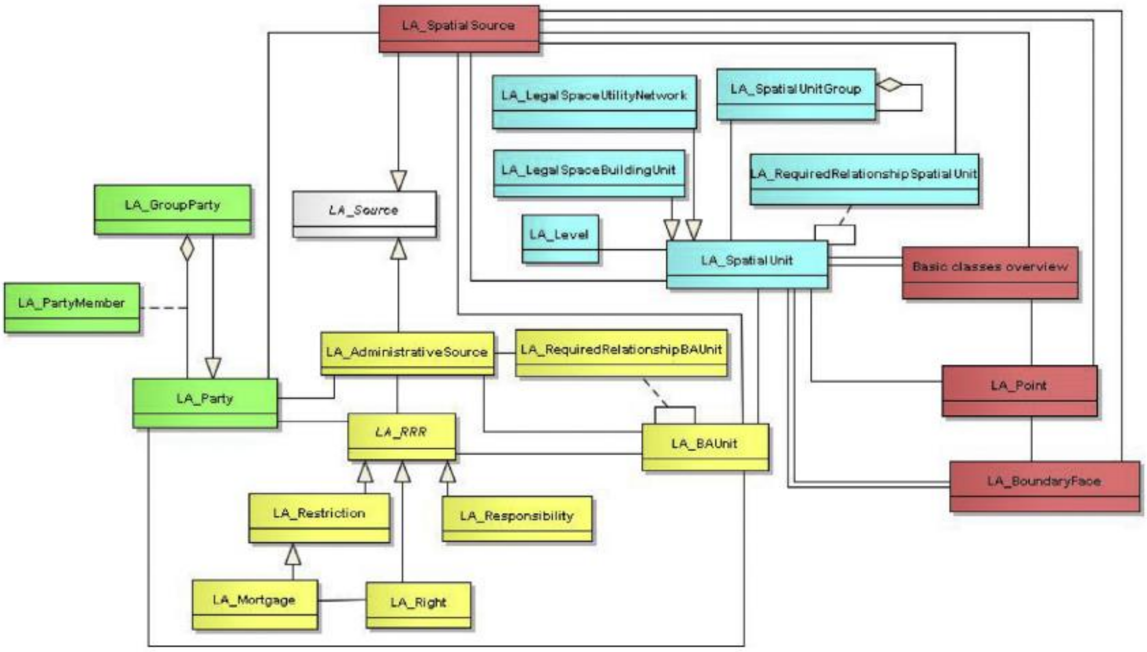


Figure 1. Overview of the Land Administration Domain Model (Source: Lemmen et al., 2015).

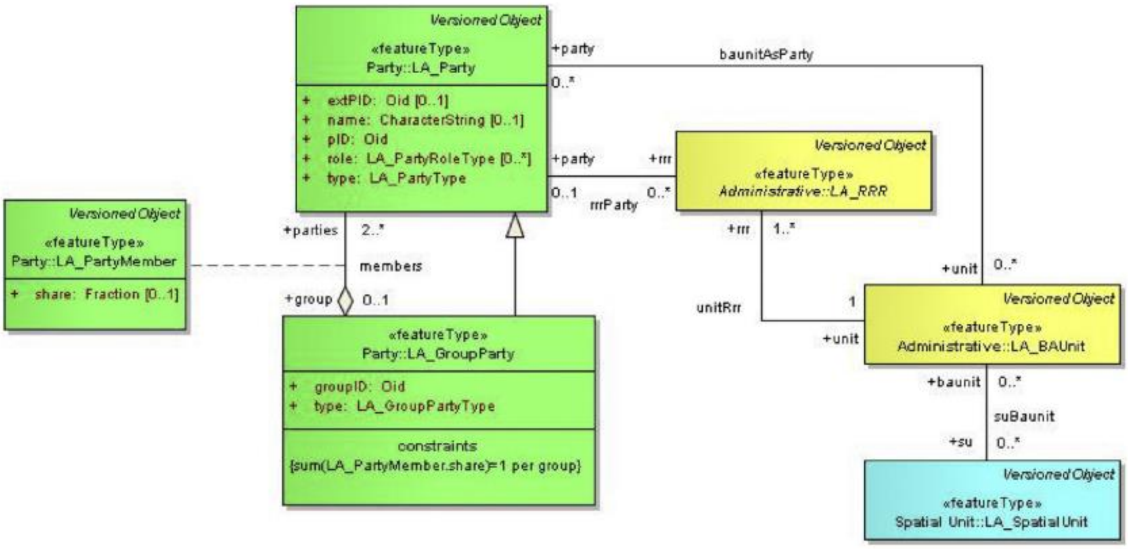


Figure 2. Overview of Party Package (Source: Lemmen et al., 2015).

Each package includes a number of classes aiming to cover and describe all possible ownership statuses. Their content may be briefly described as follows:

- Party package. The main class of the Party package is LA_Party class with its specialisation LA_GroupParty and an optional association class named LA_Party-Member. A ‘Party’ may be a person or an organisation that has a certain role in a rights transaction. Respectively, a ‘Group Party’ consists of a number of parties, representing a solid entity, while a ‘Party Member’ represents a registered party with the role of a constituent of a group party (Figure 2).
- Administrative package. The first class contained in this package is the LA_RRR class, referring to the Rights, Restrictions and Responsibilities associated with a property/spatial unit. LA_RRR class composed of three concrete subclasses, namely

LA_Right, LA_Restriction and LA_Responsibility. The second class included in the Administrative package is the LA BAUnit (Basic Administrative Unit) class. An LA_BAUnit is an administrative entity composed from zero or more spatial units, against which one or more unique and homogeneous RRR are associated to the whole entity as included in the land administration system (Figure 3).

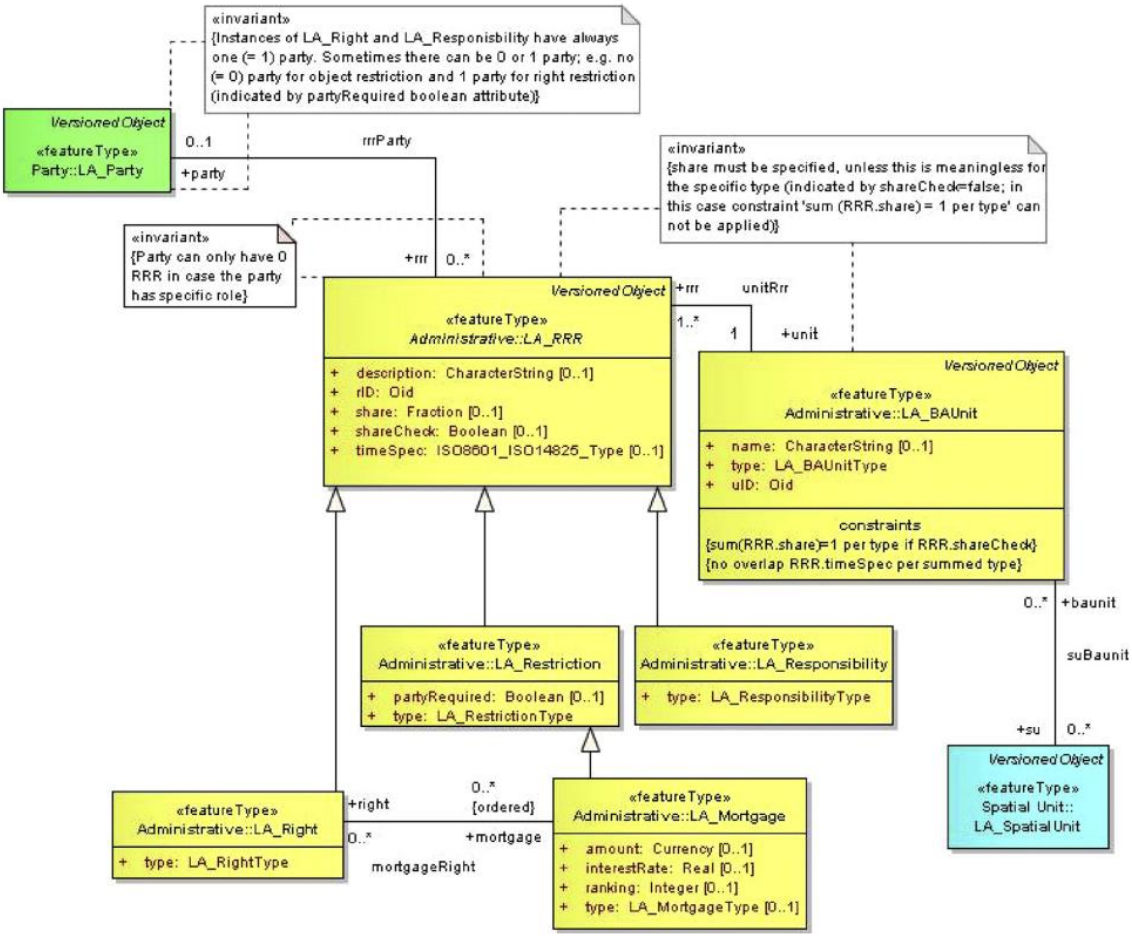


Figure 3. Overview of Administrative Package (Source: Lemmen et al., 2015).

- Spatial Unit package. The spatial unit package refers to classes representing an area of land (parcel) and/or water or a volume of space, as well as the relationships between them (Figure 4). Spatial Units are of great importance as they support both the creation and management of basic administrative units. The main classes included are the classes LA_SpatialUnit, LA_SpatialUnitGroup, LA_Level, LA_LegalSpaceNetwork, LA_LegalSpace-BuildingUnit and LA_RequiredRelationshipSpatialUnit. A 'Spatial Unit' can be represented as a text (descriptive designation), a point (or multi-point), a line (or multi-line) representing a single area (or multiple areas) of land or water or even, a single volume of space (or multiple volumes of space). Furthermore, a 'Spatial Unit Group' consists of a number of spatial units, which may represent an administrative zone (e.g., a municipality, a department etc.) or a planning area. Finally, LA_Level class refer to a set of spatial units with a geometric and/or topologic and/or thematic coherence.Surveying and Representation sub-package (Figure 5). Beyond the abovementioned classes, the Spatial Unit Package has also a sub-package entitled Surveying and Representation. This sub-package includes the LA_SpatialSource, LA_Point, LA_BoundaryFaceString and LA_BoundaryFace classes, aiming to set a valid georeference and describe properly both 2D and 3D spatial units. The data included in these classes, and more specifically LA_Points, may be acquired in the field by classical surveys or from images with photogrammetric techniques. However, these measurements and observations consist an attribute of LA_SpatialSource.

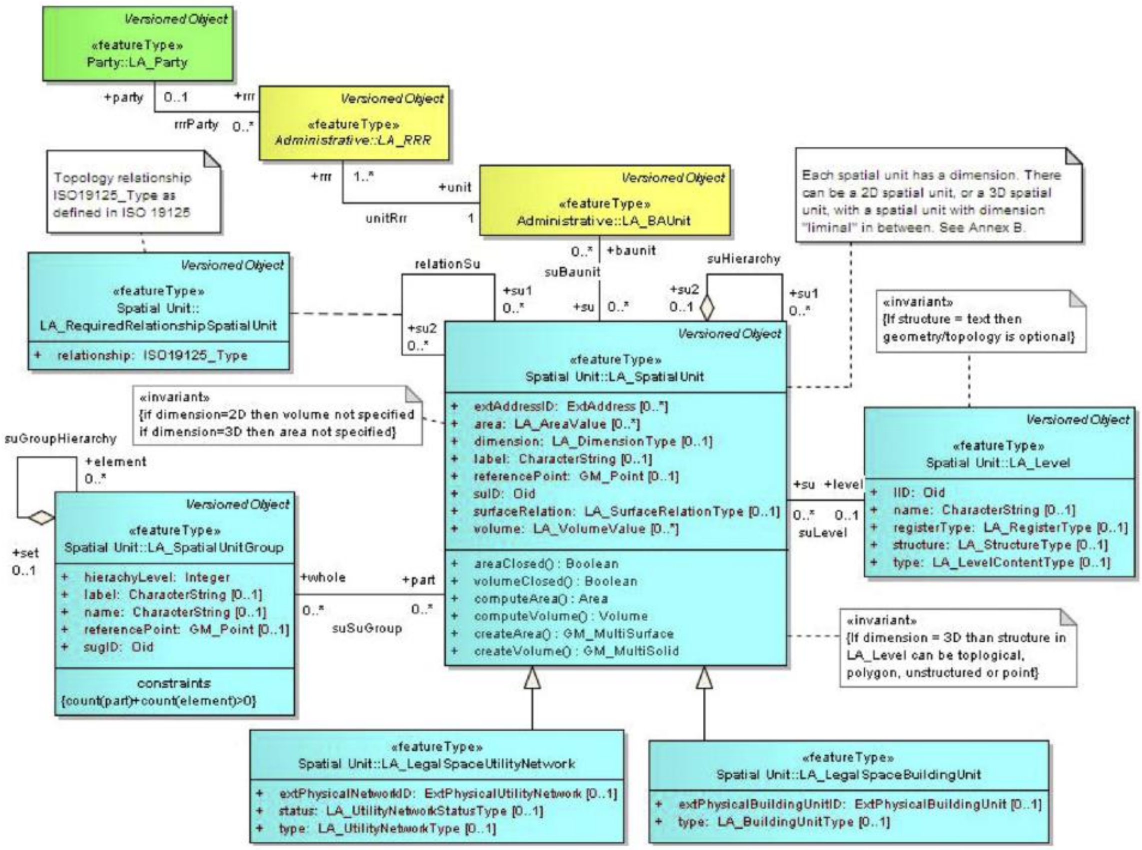


Figure 4. Overview of Spatial Unit Package (Source: Lemmen et al., 2015).

One of the most critical parameters concerning the utilization of LADM for the development of an efficient 3D cadastral system is the creation of the 3D cadastral geometric objects. The Spatial Unit package and the Spatial Representation and Survey sub-packages include several representations for 2D and 3D cadastral data (sketch, point, text, unstructured line, polygon and topological based spatial unit). According to LADM, a "true" 2D representation of a spatial unit consists of a boundary face string, known as LA_BoundaryFaceString, while a "true" 3D representation of a spatial unit consists of arbitrary oriented faces, known as LA_BoundaryFace (Figure 6). An LA_BoundaryFaceString may be represented using a GM_MultiCurve (linestring), while an LA_BoundaryFace may be represented using a GM_Surface (that may be curved). Based on ISO 19107 (ISO, 2008) a GM_Surface is composed of two (closed) GM_Curves, which are composed on several GM_Points (Figure 7). Thus, a set of GM_Surfaces with upper and lower boundary faces, may be consider as a valid 3D representation of a cadastral object. In the absence of upper and lower boundary faces, the so-called liminal spatial units are formed, which are on the threshold of 2D and 3D representations. These representations are a combination of boundary face strings and vertical boundary faces, which theoretically extend to the unlimited.

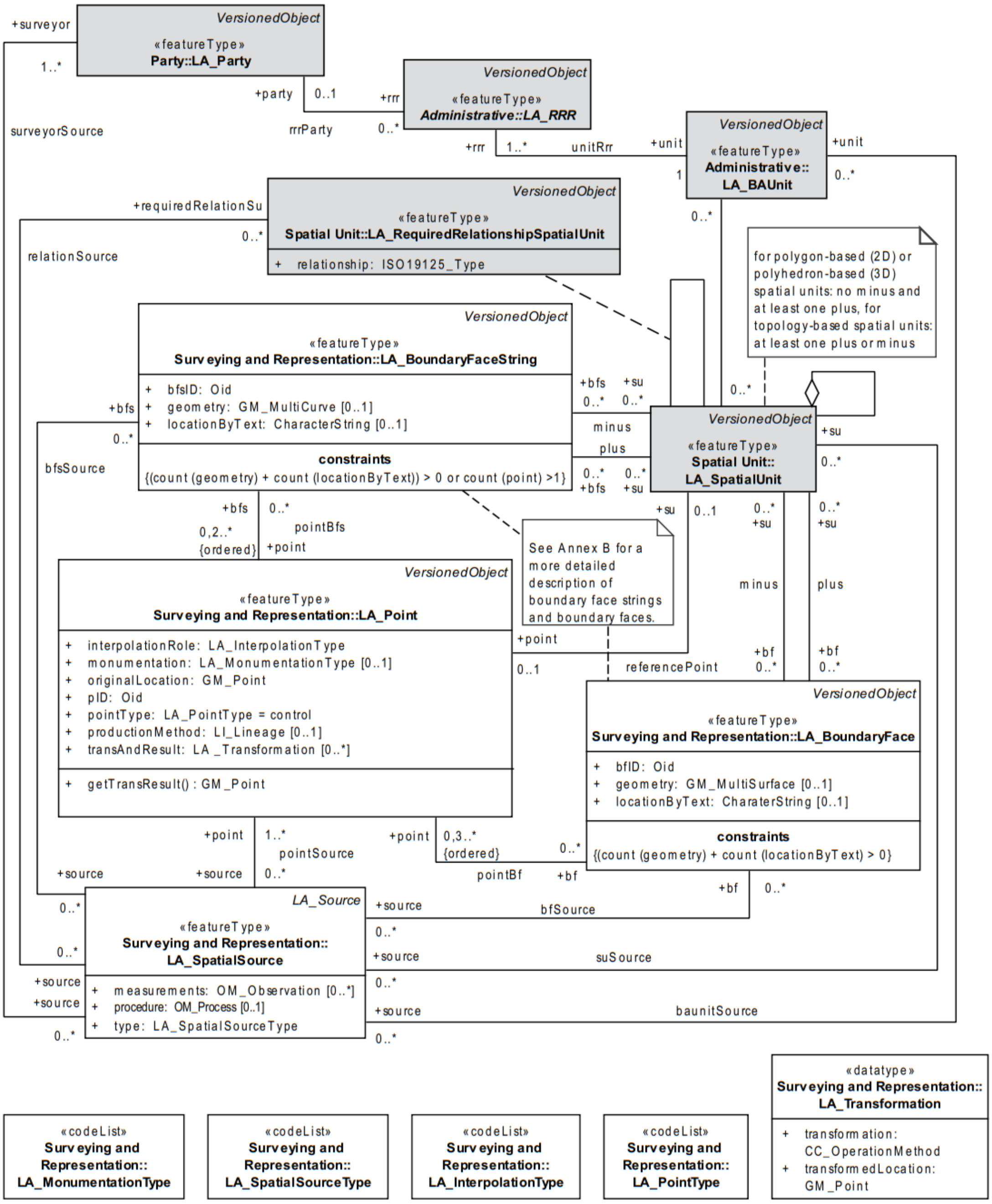


Figure 5. Overview of Surveying and Representation Sub-package with associations to the other (basic) classes (Source: Lemmen et al., 2015).

Furthermore, LADM provide several code lists for each one of the three main packages (Figures 8, 9, 10, 11). Code lists are useful for expressing a long list of potential values. Through the use of these code lists LADM aim to allow the use of local, regional or national terminology. Of course, each user community has to define and manage its own values when implementing this International Standard.

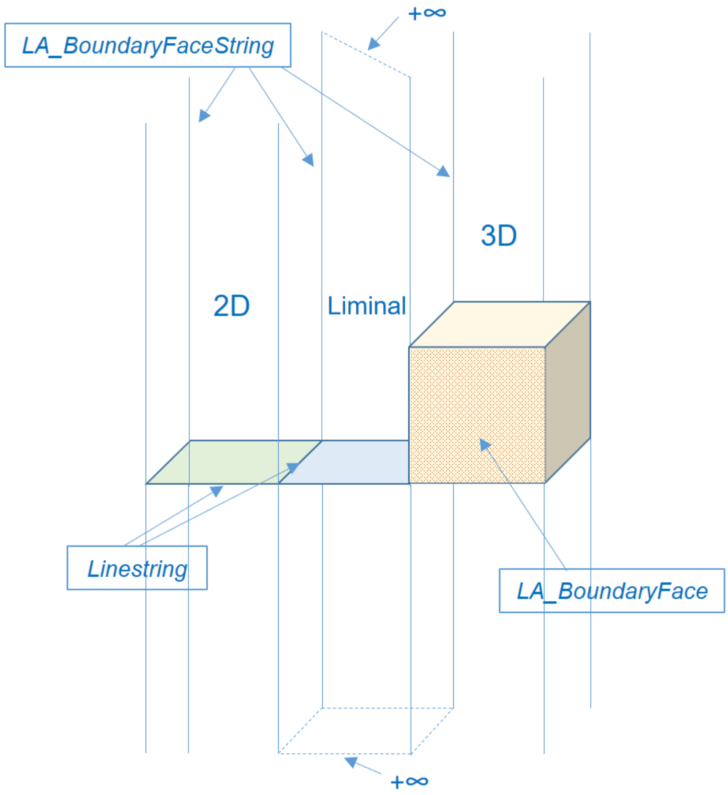


Figure 6. Side view of the mixed use of boundary face strings and boundary faces to define both bounded and unbounded 3D volumes.

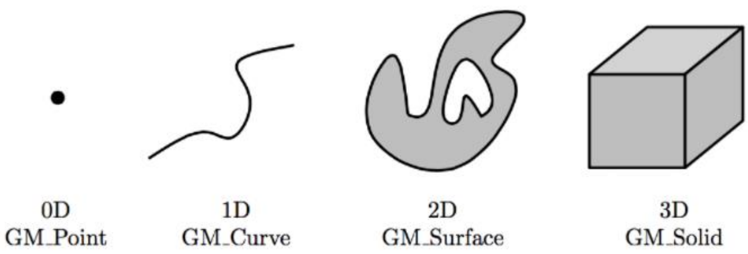


Figure 7. Overview of Spatial Unit Package.

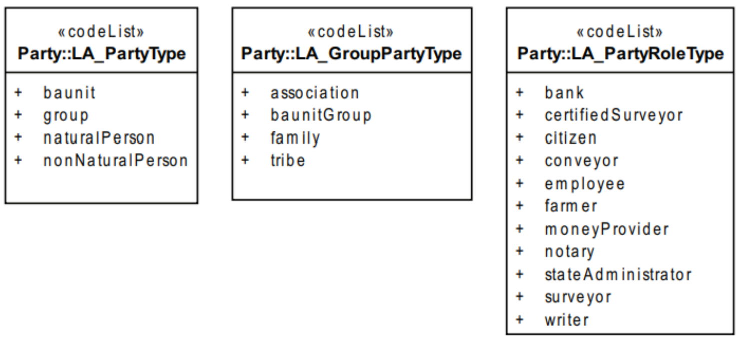


Figure 8. Code lists for Party Package.

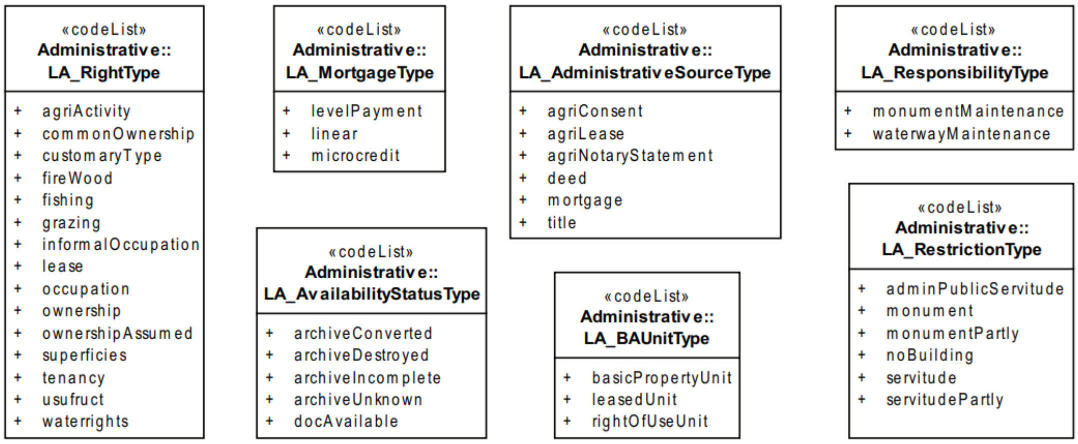


Figure 9. Code lists for Administrative Package.

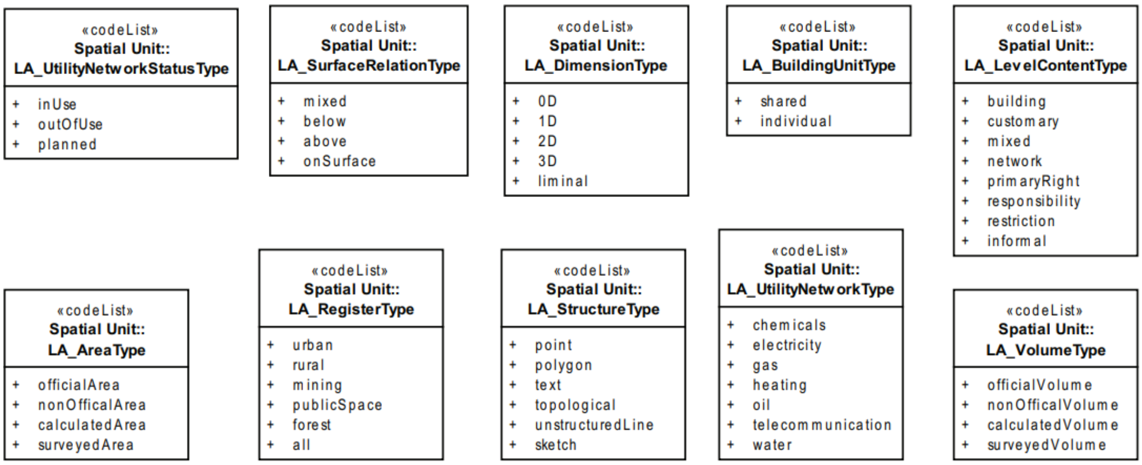


Figure 10. Code lists for Spatial Unit Package.

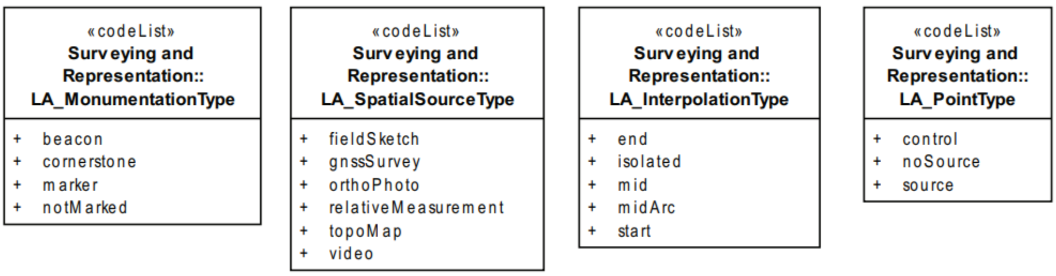


Figure 11. Code lists for Surveying and Representation Subpackage.

Besides the main packages of LADM, there are also other important classes that should be mentioned. VersionedObject class consist a valuable class of LADM, which is inherited from the majority of LADM's classes, and aims to manage and maintain historical data in the database (Figure 12). All the inserted data, are given a time-stamp, enabling the database to be reconstructed at any historical moment. Also, LA_Source class consists an abstract class composed from two subclasses, the LA_AdministrativeSource, and the LA_SpatialSource class, retaining the administrative and spatial sources, respectively. Furthermore, LADM enables the utilization of external links with other databases (e.g., addresses), supporting information infrastructure type of deployment.

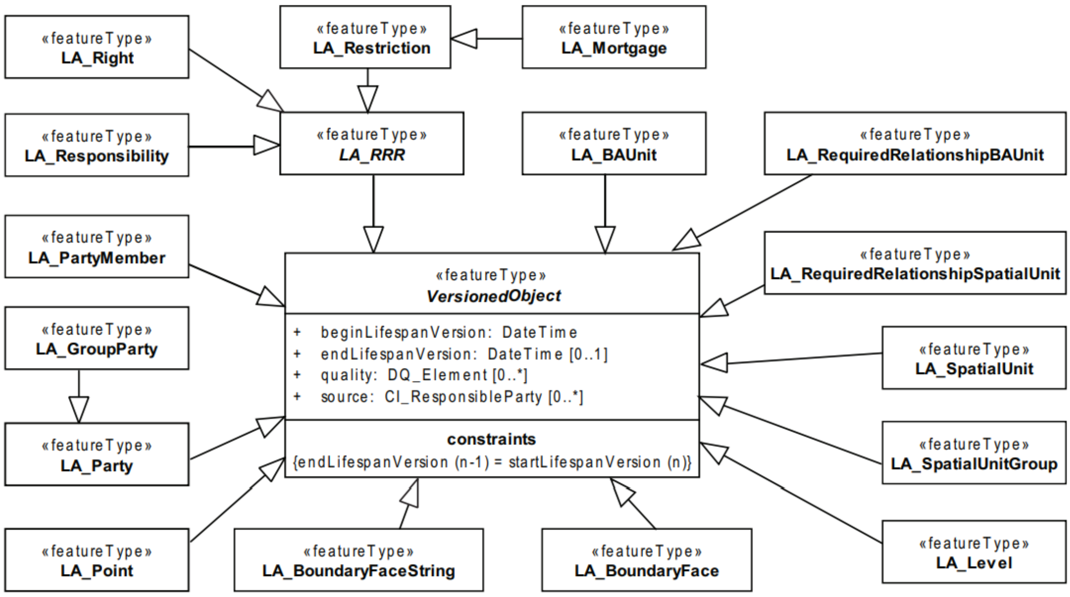


Figure 12. Classes of VersionedObject.

The implementation of LADM can be performed in a flexible way, as the draft standard conceptual schema can be extended and adapted to local situations. However, it is worth mentioning that while LADM provide a generic framework for 3D cadastres, the identification of the acceptable 3D geometries and representations for the 3D cadastral objects are still challenges (Ying et al., 2015).

2.3 3D LADM-based country profiles

Among various investigations concerning several prototype systems and approaches for the implementation of 3D cadastres, those based on LADM standard are of particular interest. In this section some of them have been selected and presented. Each one of the proposed/developed country profiles handle the 3D aspect according to the current legislation and cadastral background.

2.3.1 Russian Federation

One of the first pilot LADM-based country profiles started in 2010 by the Russian Federation, with a project entitled "Modelling 3D Cadastre in Russia". The initial cadastral prototype emphasizes the visualization of 3D information of the cadastral objects as polyhedrons, while a web-based browser solution has been developed. The model was adapted to the Russian environment and oriented to five types of property: land parcels, buildings, premises, structures and unfinished construction projects (Figure 13). It is highlighted that special attention should be given to the management of legal versus physical cadastral objects. The registration of the legal objects - which in this case concern the cadastral parcels where the RRR are referred - and their physical counterparts (building units or underground constructions) generate two different but related databases. The visualization of the physical objects is valuable in order to provide a clear understanding regarding the location and size of the legal objects. In this pilot study, CityGML was integrated with 3D LADM, aiming to connect the 3D cadastral objects with their respective physical counterparts (building units) (Vandysheva et al., 2011).

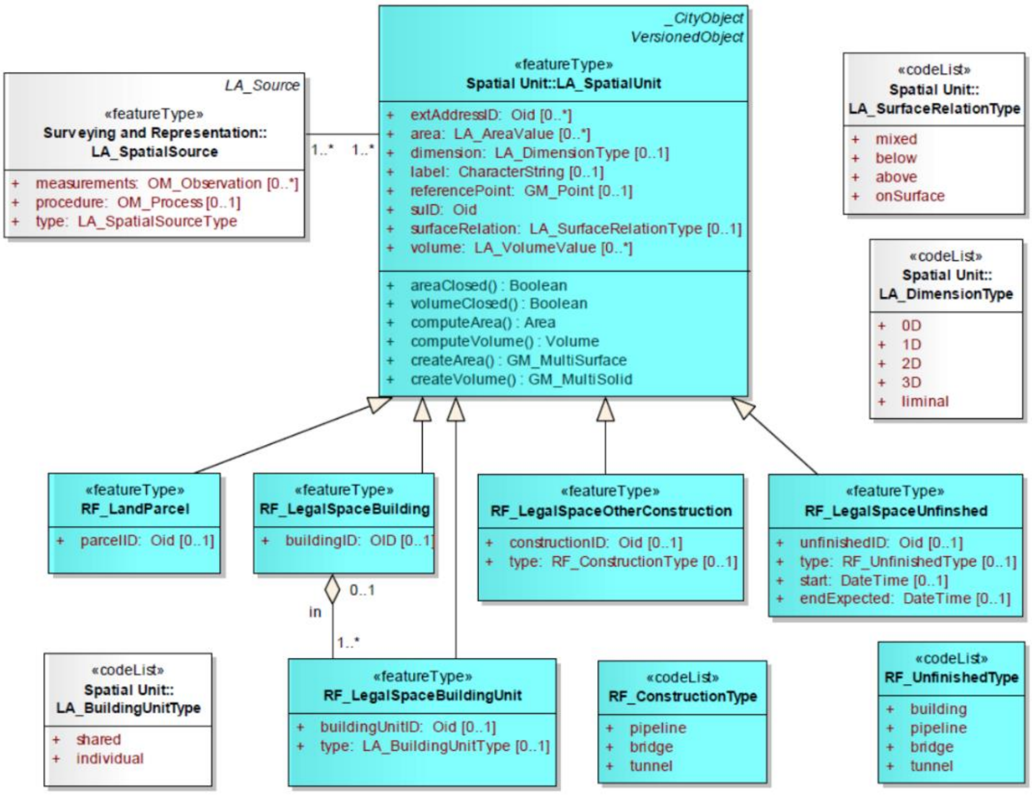


Figure 13. The initial Land Administration Domain Model (LADM) for the 3D cadastre pilot project in the Russian Federation (Source: Vandysheva et al., 2011).

2.3.2 Poland

A 3D LADM-based Polish country profile was proposed by Góźdź & Pachelski (2014). The proposed model introduced two new classes, representing buildings, in order to proceed with the registration of the 3D cadastral objects. For the implementation of the proposed model a CityGML-LADM Application Domain Extensions (ADE) was created aiming to establish the link between the legal and physical counterparts. The model also provided an association between a building (or a building part) and a 3D cadastral parcel, which is useful when a building (building part) has its own specific RRRs attached. In order to solve the main difficulty of the current cadastral system, when dealing with 3D overlapping property rights, they propose the extension of LADM's Spatial Package with several new classes, as shown in Figure 14. Subsequently, Góźdź & Oosterom (2016) proposed a similar but more detailed model for the Polish country profile based on LADM. To emphasise the possibility of adding information being outside the scope of LADM, new UML classes were created representing the physical utility network data. Thus, a general insight into how LADM may be extended for specific applications is presented.

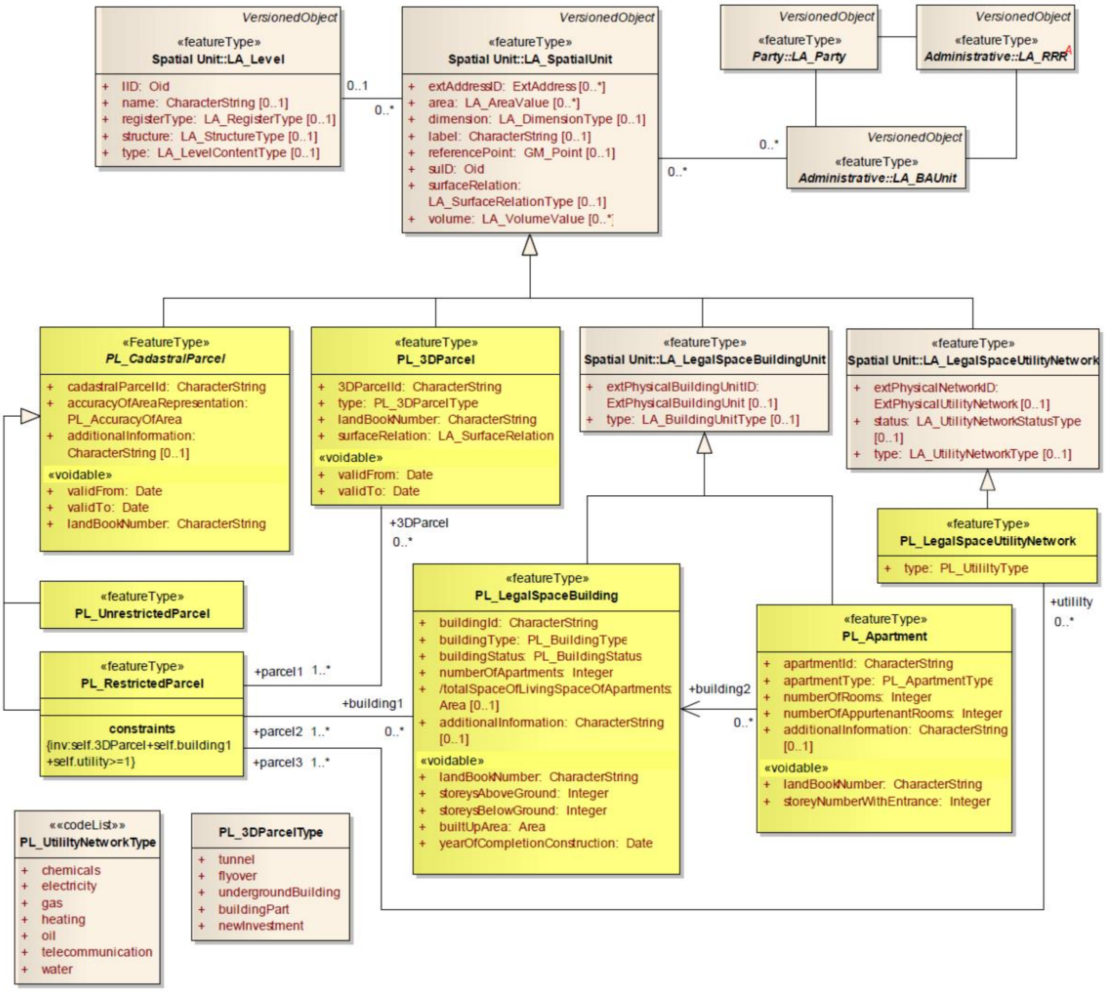


Figure 14. Spatial package of the Polish 3D LADM country profile (Source: Góźdź & Pachelski, 2014).

2.3.3 Korea

An interesting approach was developed by Lee et al., (2015), who proposed a 3D land administration model for Korea using a cadastral resurvey form, including the representation of 3D physical properties and 3D rights. The new cadastral model supports 3D information as it can contain underground utility and superficies information to present the physical and legal information on both buildings and underground features. New classes added to LADM in order to provide an efficient description and representation of the 3D physical and legal cadastral objects, such as individual residencies, rooms in a building, utility networks and their own legal space respectively. The new suggested country profile for Korea is shown in Figure 15.

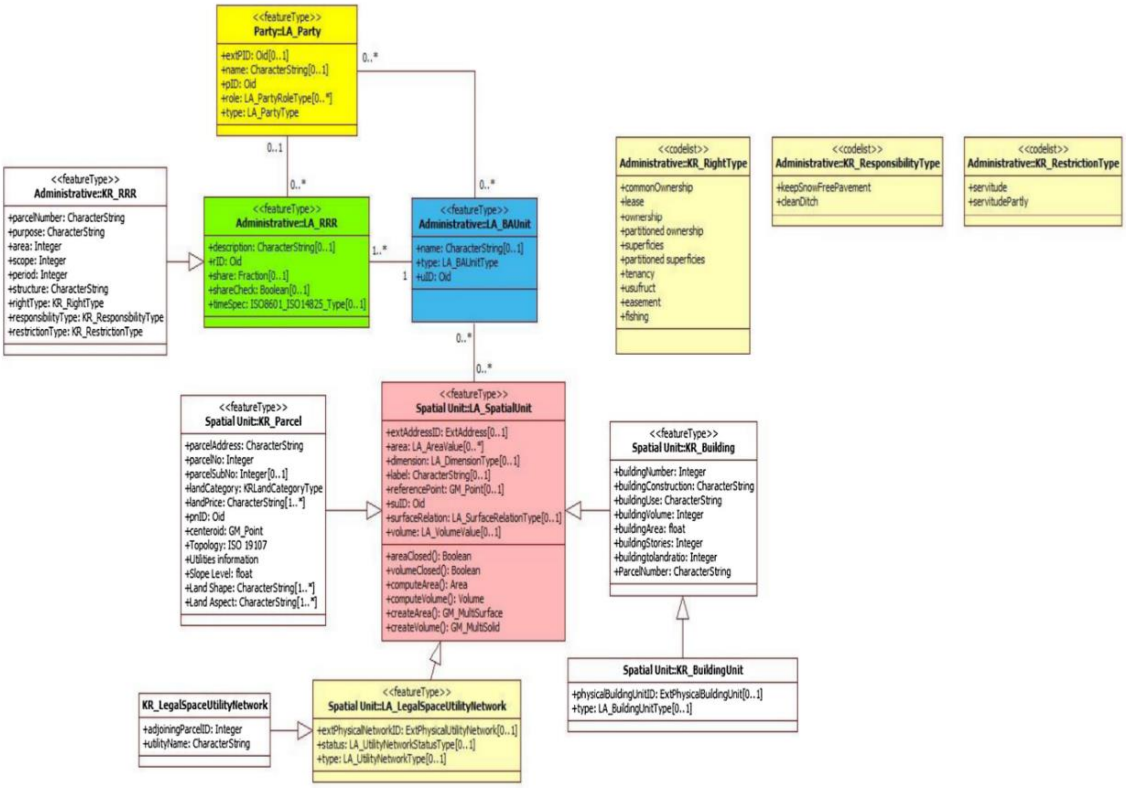


Figure 15. Korean 3D LADM country profile (Source: Lee et al., 2015).

2.3.4 Greece

In Kalogianni (2015), a different LADM-based country profile was proposed utilizing the concept of LA_Level. This prototype system was developed based on model-driven architecture practices utilizing INTERLIS language and tools. The country's spatial units are categorized and organized in different levels (Figure 16). A new class (GR_Level) is introduced, allowing the efficient management and representation of data according to their level. Within the proposed model, an attempt is made to cover all Greek land administration related information, which are currently maintained by different organizations. The model was adapted to the Greek environment and oriented to several different types of spatial units including: areas with archaeological interest, buildings and unfinished constructions, utilities (legal spaces), 2D and 3D parcels, mines, planning zones, Special Real Property Objects (SRPO) usually found in Greek islands (anogia, yposkafa) and marine parcels. In order to integrate the 3D legal aspect with the corresponding physical reality of the 3D objects, an alternative structure for the GM_Solid is proposed, as INTERLIS structures describe only 2D objects. Furthermore, the country profile is enriched with various code lists that are an important for standardization.

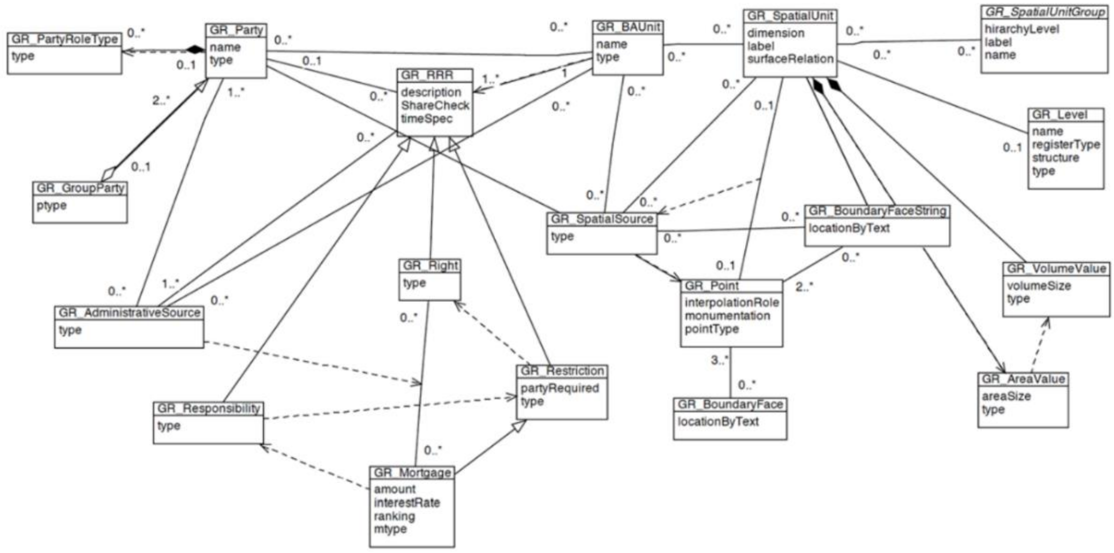


Figure 16. Proposed 3D Greek LADM country profile (Source: Kalogianni, 2015).

2.3.5 Malaysia

Several interesting approaches have been proposed for the Malaysian LADM-based country profile in previous years (Zulkifli et al., 2014; Zulkifli et al., 2015). For both the private and the public land, the main subdivision of land in Malaysia is based on lots, with 2D or 3D representations. The term ‘lot’ may be confused with the term ‘parcel’, which in case of Malaysia has not the same meaning as in several continental European countries. Figure 17 illustrates in detail the different types of strata objects in Malaysia (Oosterom et al., 2018). The Malaysian profile includes support for strata objects and 3D spatial unit representing building, utility and lot (Figure 18). Furthermore, Rajabifard et al. (2018) proposes strategies for the implementation of 3D Malaysian National Digital Cadastral Data Base (NDCB). The investigation focuses on the processes for upgrading the existing dataset and data collection methods in order to support the 3D digital data and the creation of 3D spatial database based on the elicited user requirements.

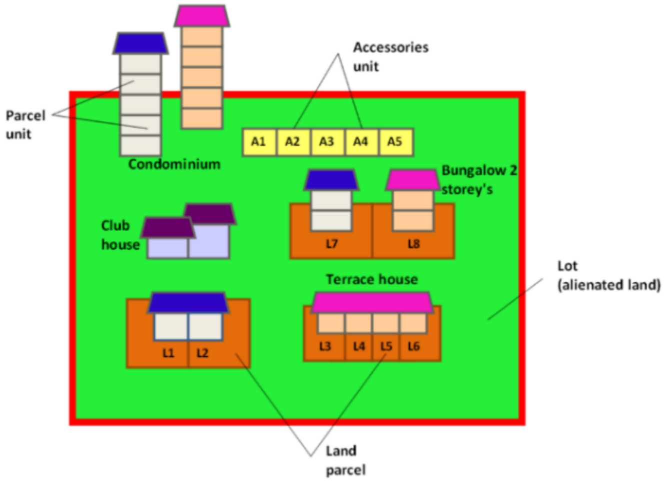


Figure 17. Different types of cadastral objects related to strata titles within a lot (Source: Oosterom et al., 2018).

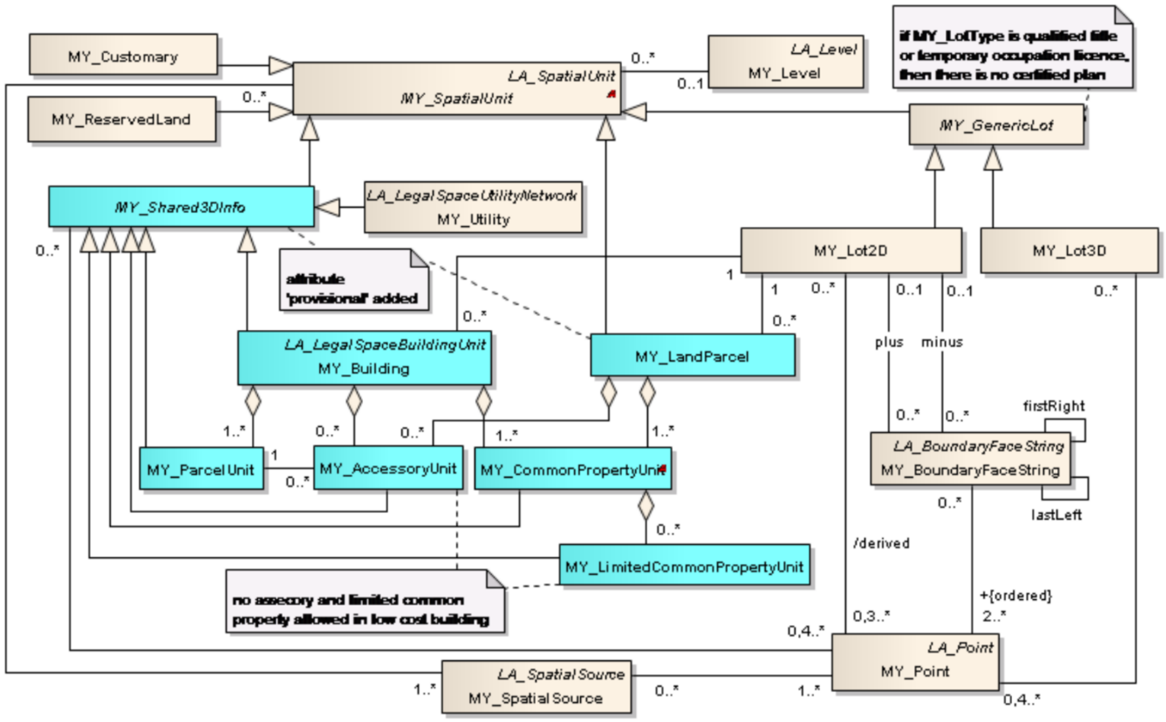


Figure 18. Overview of the spatial part of the Malaysian LADM country profile (Source: Zulkifli et al., 2014).

2.3.6 Morocco

Adad et al. (2020) proposed a LADM-based country profile for Morocco aiming to provide a common terminology for the Moroccan land administration. The main objective was to enable a shared description of the different formal or informal processes, and to allow the combination of land administration information from different sources. In Morocco, all the cadastral mapping is implemented in 2D, but there are some records that demonstrate the 3D aspect of properties, such as the number of the floors, the elevation dimensions etc. However, the Moroccan land system does not explicitly include 3D space, despite the fact that the properties are perceived in 3D. Currently, the cadastral plan in force in the Moroccan formal titling system represents the superficies of the horizontal projection of land parcel. As the elevations of the points that delimit a parcel might be at different level, the real superficies may be lower or higher than the adopted one in the plan and for the title.

Considering these remarks, the MA-LADM country profile of Morocco was generated (Figure 19). In the developed MA-LADM profile a specialization of LA_SpatialUnit class was made in order to allow the creation of 2D spatial units (MA_2dHorizonalProjectionBasedParcel) and 3D spatial units (MA_3dReal SuperficieBasedParcel, MA_3dCondominiumUnit18-00, MA_3dCondominiumTouristicUnit01- 07, MA_3dNonCondominiumBuilding, MA_3dLegalSpaceUtilityNetwork, MA_3dLegalSpace UtilityNetwork, MA_3dCondominiumPrivatePart and MA_3dCondominiumSharedPart). This specialization considers both the individual or shared ownership of buildings as well as those covered by condominium restrictions (Adad et al., 2019c). Furthermore, to overcome the abovementioned elevation drawback, a new class entitled MA_3dRealSuperficieBasedParcel was generated in order to permit the calculation of the area by adding the superficies of the triangles composing the whole parcel using its modeling as a triangulated irregular network (TIN).

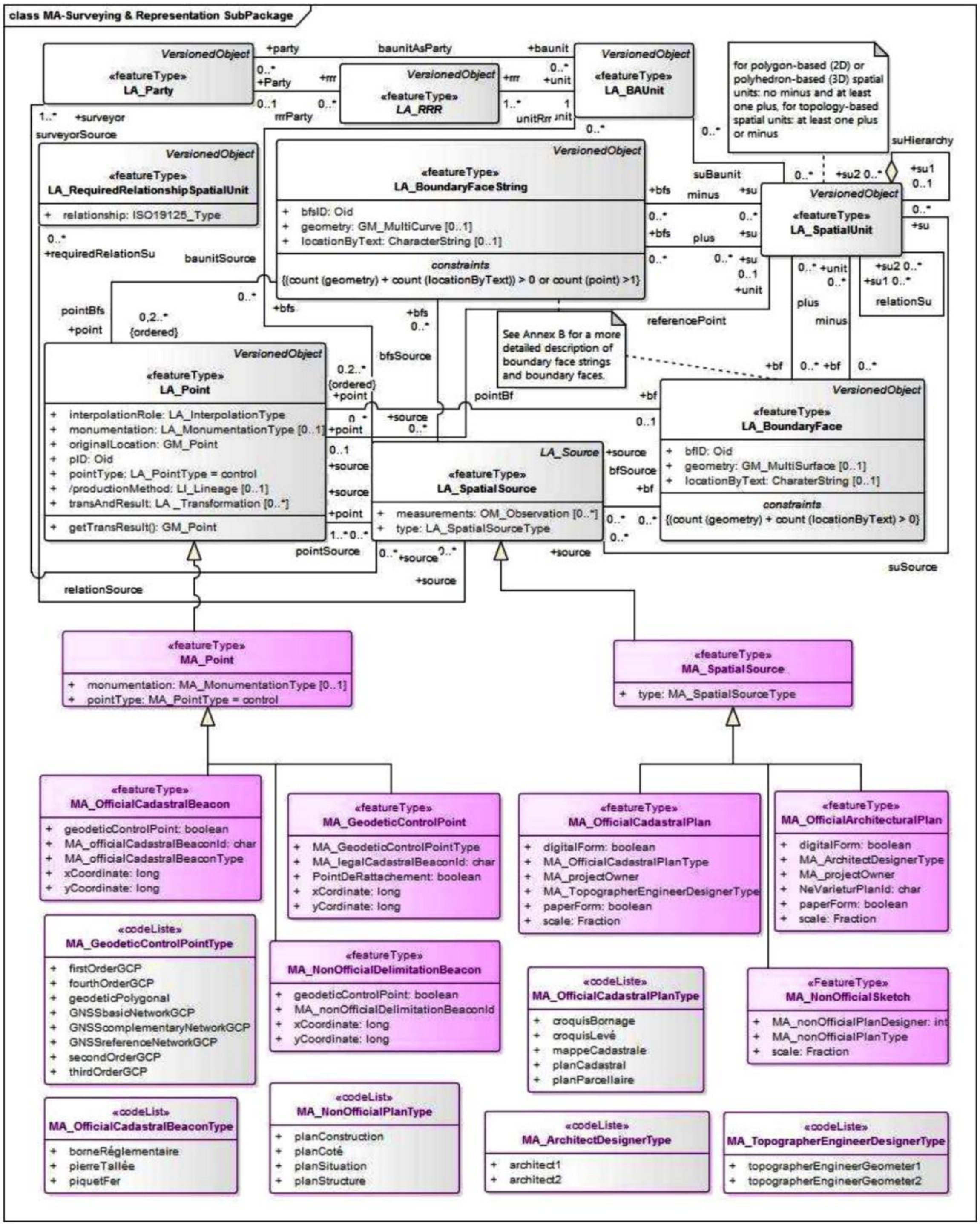


Figure 19. Overview of the *MA-LADM surveying and representation sub-package* (Source: Adad et al., 2020).

2.3.7 Saudi Arabia

The development of the country profile of Saudi Arabia has passed through several phases, and it started with the development of the initial country profile. The initial country profile was created based on the interaction between all stockholders in order to represent Saudi Arabia's land administration system (Alattas et al., 2019). In Saudi Arabia, building unit subdivision processes are based on a 2D representation of legal space ownership. The 3D depiction of legal space ownership, on the other hand, will provide a more detailed description of the spaces for better registration. As a result, the 3D depiction of legal space ownership has been proposed by applying the same laws and regulations as Saudi Arabia's existing building unit subdivision processes (Alattas et al., 2021). The 3D representation of legal space ownership was utilized to convert the 2D country profile into a 3D country profile that contains all of the new attributes that have been linked to the 3D model as detailed in (Alattas et al., 2021).

Alattas et al. (2021) exploit the current trend of designing new buildings directly in BIM and propose the re-use of those BIMs for cadastral purposes. Alattas et al. (2021) provide a mapping from the BIM/IFC to LADM, both at conceptual modelling and at the level of the individual units with their geometry and topology (Figure 20). The proposed mapping requires the BIM/IFC file to contain sufficient information in order to enable the identification of the different spaces being part of a property.

Three different main type of spaces were identified: the private part, common part, and the exclusive common part. The administrative packages SA_BAUnit, SA_Right, and SA_Party classes include new properties which correspond to the additional information required to establish the ownership of the spaces and construction components. The SA_SpatialUnit is an abstract class with three more attributes from the ISO 19152:2012 UML: districtNo, districtName, and city. The SA_Level class is used to represent the three property description levels: level zero for parcels, level one for building units, and level two for construction components.

The SA_ConstructionElement class is abstract and has a generalization relationship with the SA_SpatialUnit class. There are three subclasses of the SA_ConstructionElement: SA_Wall, SA_Column, and SA_Slab. Additionally, the SA_Building class has a generalization relationship with the SA_SpatialUnit, and it contains three extra attributes from the ISO UML: reference, type, and numberOfFloor. Furthermore, the SA_Building class is composed of the SA_ConstructionElement class. The SA_BuildingUnit class is abstract and represents the building's spaces; it contains three subclasses: SA_MainUnit, SA _AmenitiesUnit, SA_SharedAreaUnit, and two more attributes are added: floorNo and area. The SA_MainUnit class represents the most common type of space and has five attributes: type, propertyNo, percentageOfThePropertyAreaToTheParcelArea, propertyShareFromTheParcelArea (Sq.M), and ownershipBoundary. The attribute 'type' takes values from the code list SA_UnitType, representing various unit types such as office, apartment, shop, and clinic. The service spaces are represented by the SA_AmenitiesUnit class, which contains three attributes: type, AmenitiesUnitNumber, and AmenitiesUnitLevel.

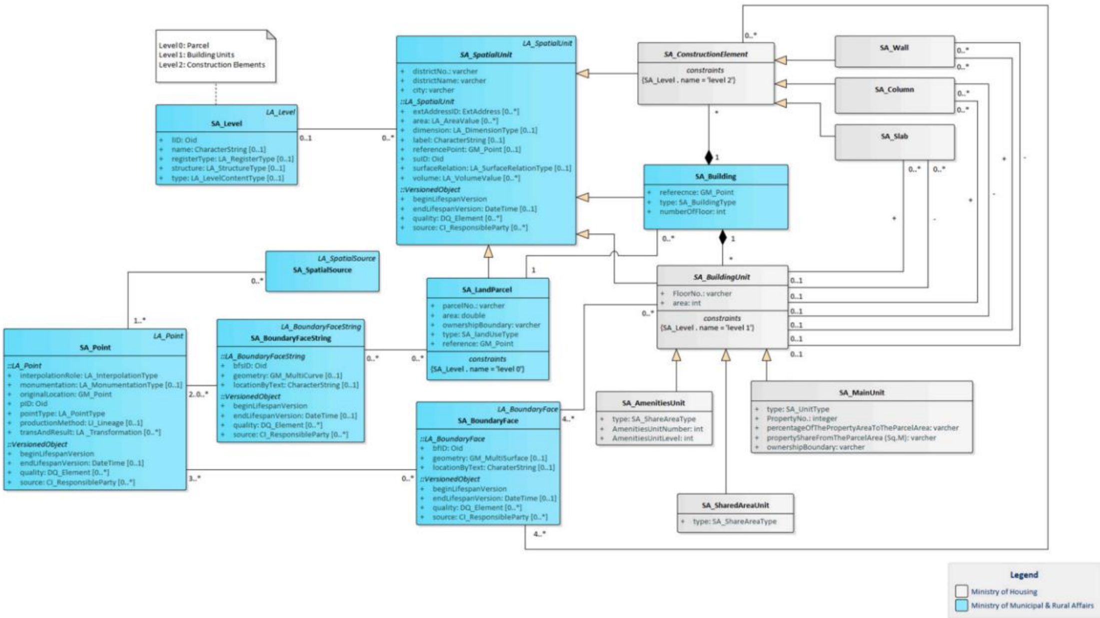


Figure 20. The spatial package of the 3D LADM Saudi Arabian country profile (Sourve: Alattas et al., 2021).

2.3.8 Turkey

Recently, Gürsoy Sürmeneli et al. (2022a) proposed a Turkish country profile that meets the needs of a four-dimensional (4D) cadastral system. Their primary focus was the registration of 3D cadastral objects together with time attributes in the 3D cadastral database system. Subsequently, Gürsoy Sürmeneli et al. (2022b) developed an innovative ADE 4D Cadastral Data Model for depicting the cadastral rights in 3D using LADM and CityGML. The data management were done in an open-source database for the Turkish cadastral system. The physical details corresponding to the legal attributes' information, were modelled with LADM and then linked with CityGML through a new ADE. Then a 4D database was created using PostgreSQL, in order to visualise the cadastral information at the building level. Finally, the CesiumJS platform was utilized for the visualization and temporal analysis on a city scale.

In order the Turkish ADE 4D Cadastral Data Model to be created, a set of new classes and corresponding attributes were added to the CityGML LandUse and AbstractBuilding feature classes. In summary, five new feature classes have been specified as the AbstracBuilding class's subclasses. These are entitled TR_CondominiumUnit, TR_Building, TR_Annex and TR_BuildingUsePart. TR_Parcel was defined as a subclass of the LandUse class. Even though CityGML does not explicitly represent parcels, the OGC specification argues that the LandUse class represents parcels as 3D.

Also, it was highlighted that since the CityGML AbstractBuilding has numerous building-related properties and code lists (such as the number of floors, roof types, year of construction and demolition, usage, and so on), it can adequately describe buildings and their subclasses in the Turkish cadastral system. However, it was considered preferable the CityGML AbstractBuilding class to be extended with more specific attributes, such as building number, building usage permit date, building license approval date, and building value for the developed model. In Figure 21 the innovative ADE Cadastral Data Model of the Turkish cadastral system is illustrated to better understand the associations between the new and existing classes.

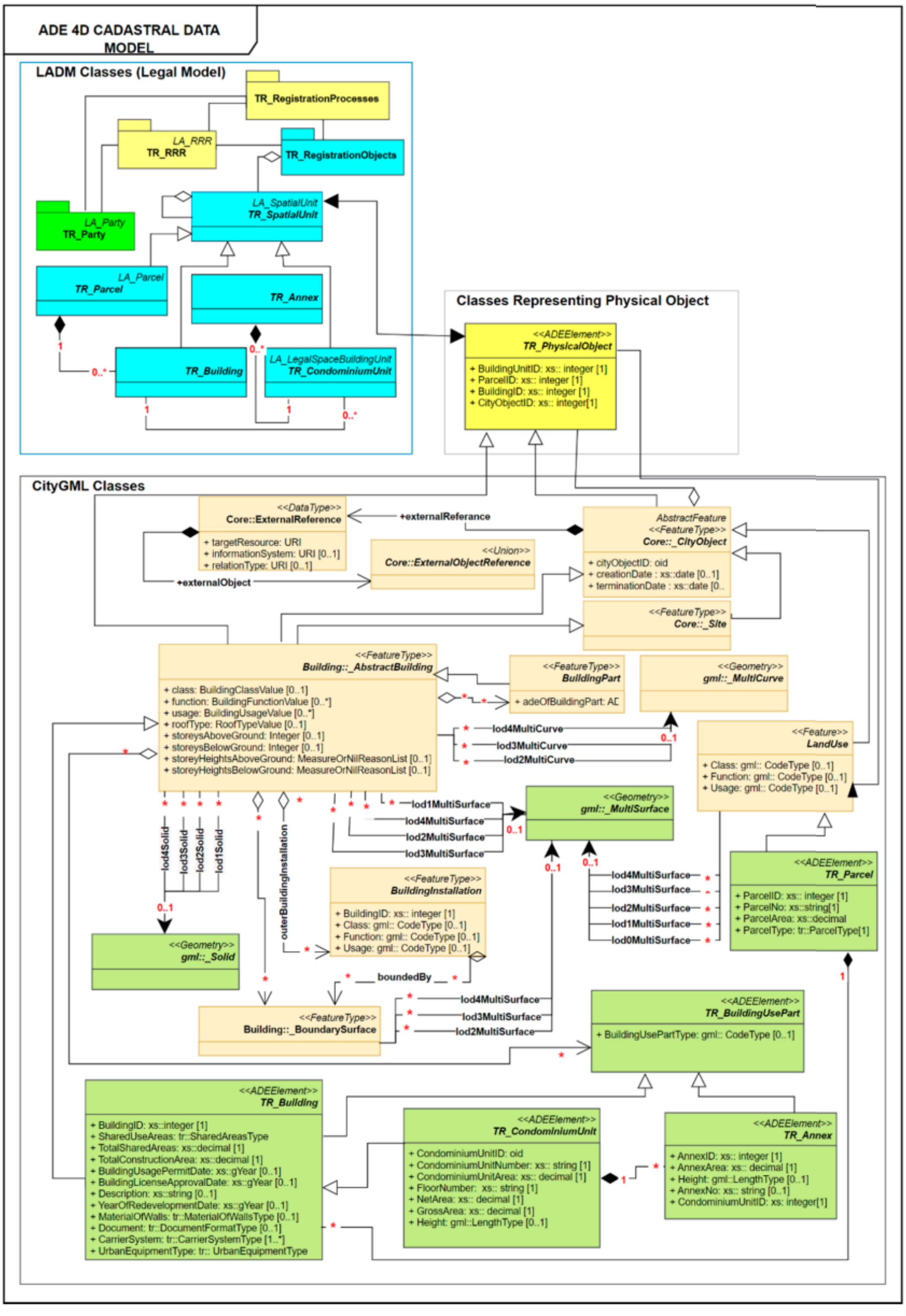


Figure 21. The conceptual model of the proposed Turkish LADM-based country profile (Source: Gürsoy Sürmeneli et al., 2022b).

2.4 Linking LADM with physical models

Through the last few years several approaches have been proposed to settle a link between the legal and physical counterparts of 3D cadastral objects. This integration is a quite new research topic in 3D digital cadastre and thus, the amount of available literature is not very broad yet. These investigations are mainly focuses on the integration between physical data models, such as CityGML, IndoorGML BIM/IFC, LandXML, InfraGML, etc., and legal data models such as LADM. Despite those pure physical models are not particularly designed for the purpose of mapping ownership rights and property boundaries within multi-level buildings, they can be harnessed or extended for representing and managing cadastral information. These models usually manage spatial and semantic information associated with physically existent objects in various levels of details.

2.4.1 CityGML

CityGML is a well-known geospatial standard that allows the interoperable exchange of 3D urban information models (Groger et al., 2012; Groger and Plümer, 2012). Additional features and object types can be added to the CityGML core model to enable the representation, management, and analysis of 3D urban models for a variety of applications (Biljecki et al., 2018). Through adding legal information to CityGML, it will be feasible to represent legal boundaries and RRR spaces within the framework of a 3D urban information model.

Soon et al. (2014) proposes a semantics-based fusion framework to integrate LADM and CityGML standard. In order to connect the legal and physical counterparts of a building, a connection between the "LA_LegalSpaceBuildingUnit" class of LADM and the "_AbstractBuilding" class and its subclasses "Building" and "BuildingPart" in CityGML, is investigated (Figure 22).

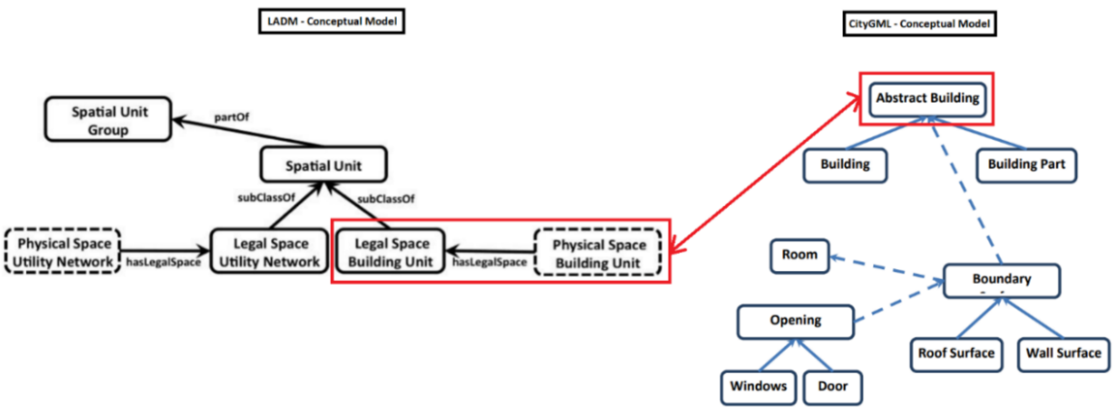


Figure 22. Proposed link between CityGML's Building module and the LADM conceptual schema (Source: Soon et al., 2014).

Ronsdorff et al. (2014) support that there are two ways to use the Application Domain Extension (ADE) mechanism in order to connect the LADM and CityGML standards. The first way focuses on a general connection between LADM and CityGML, whereas the second method considers the particulars of a specific jurisdiction's land administration when integrating LADM and CityGML. The general approach acquires the appropriate entities from LADM and incorporates them into the proposed ADE for CityGML. Ronsdorff et al. (2014), proposed an ADE where the basic administrative units (LA_BAUnit) are encoded utilizing the instantiable Parcel class. This class is linked to the LA_RRR entity to define the legal status of the Parcel. The LA_SpatialUnit class is mapped as the LegalSpace class that is associated to geometric representations in LoD0 and LoD1. The geometric representation of LoD0 is used to define surface-based spatial units, such as land parcels, while the LoD1 representation allows the volumetric representation of spatial units, such as apartment units (Figure 23).

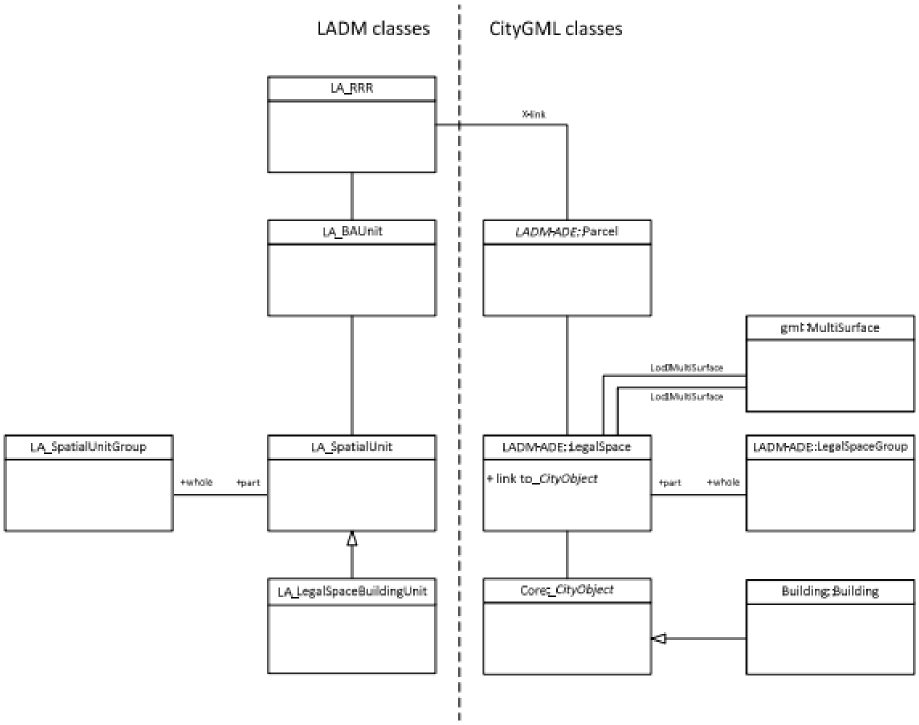


Figure 23. Feature classes in a CityGML LADM ADE and their corresponding LADM feature in simplified UML class diagram notation (Source: Ronsdorff et al., 2014).

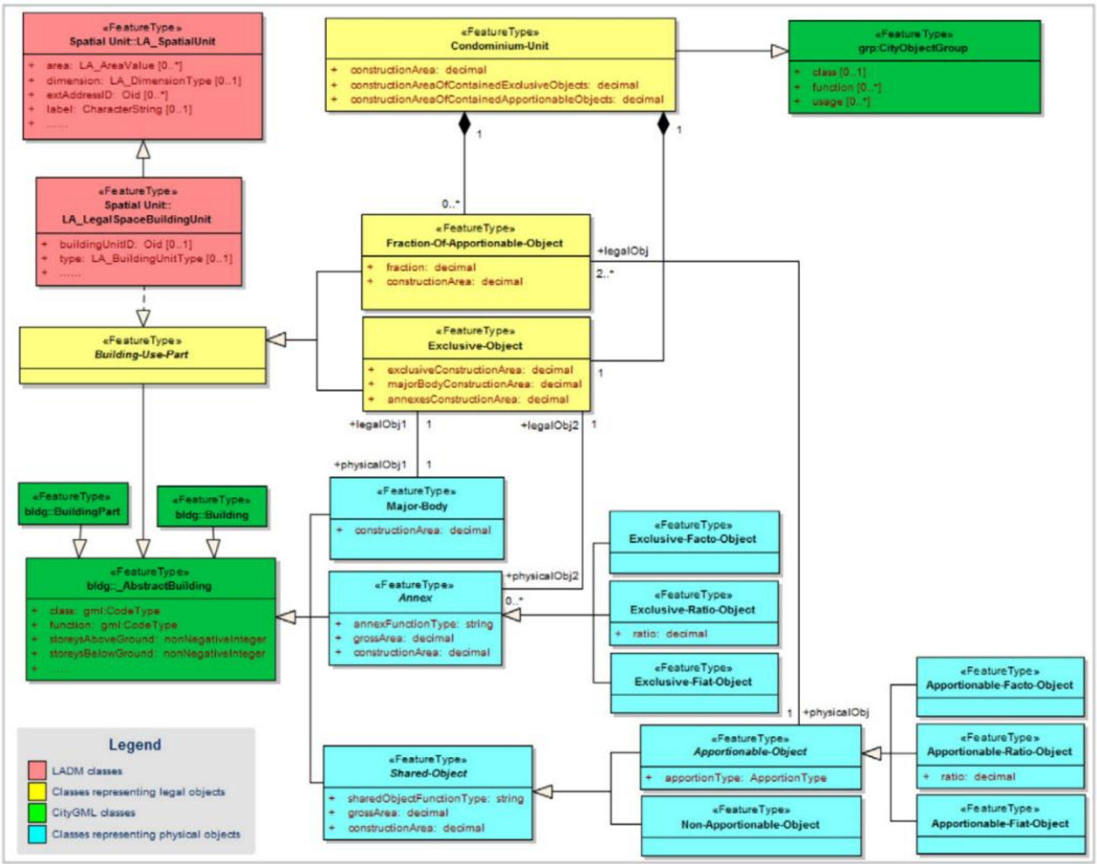


Figure 24. UML diagram of the CityGML-LADM ADE for describing the ownership structure of a condominium unit (Source: Li et al., 2016).

Li et al. (2016) developed a comprehensive LADM-based ADE comprising legal objects defined in the Chinese jurisdiction. Two separate hierarchies, a legal hierarchy (yellow color) and a physical hierarchy (light blue color), are modeled independently (Figure 24). In order to describe the ownership structure of condominium units, three main feature classes, namely Major-Body, Annex, and Shared-Object, are designed as subclasses of the CityGML abstract feature bldg.:_AbstractBuilding. This integrated model is capable of managing relationships between legal objects and physical elements and can represent ownership structure of various private and commonly owned condominium units defined in multi-level buildings.

The abovementioned investigations have attempted to link physical information, acquired from CityGML, with legal information acquired from LADM. These initiatives prompted CityGML to take into consideration land administration as one of its primary application domains. As a result, it is anticipated that CityGML version 3.0 will be more compatible with the LADM standard (Kutzner and Kolbe, 2018).

2.4.2 IndoorGML

The IndoorGML standard is widely known for its capability to provide a 3D geospatial model to support indoor navigation systems (Lee et al., 2014). In contrast to CityGML and IFC standards that describe the physical reality in general, IndoorGML is an application-oriented data model that is used for navigation in indoor environments. Zlatanova et al. (2016a) argued that connecting LADM with IndoorGML would offer an integrated method for linking physical areas and RRR data, useful for a wide variety of use cases related to indoor navigation, such as for airports, metro stations, shopping centres, including areas with different restrictions and rights (Zlatanova et al., 2016b).

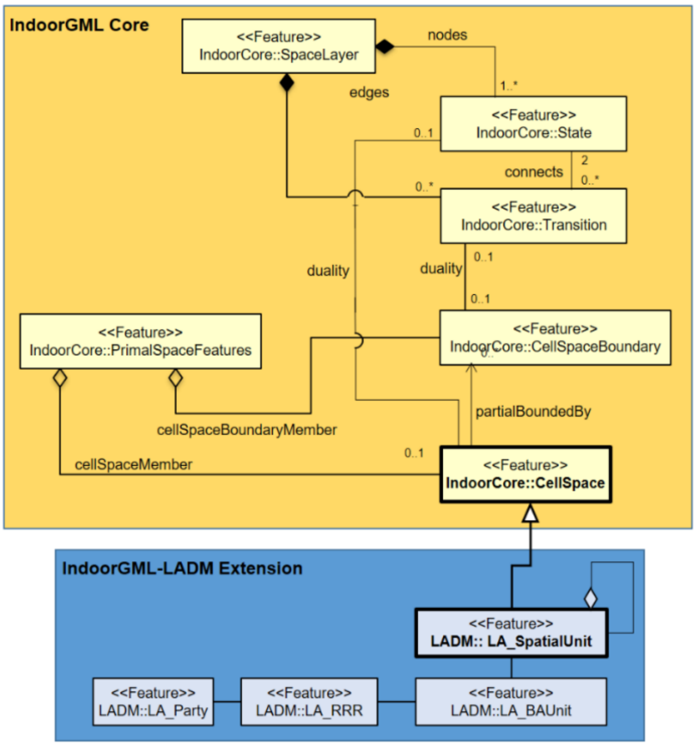


Figure 25. LADM Extension of IndoorGML (Source: Zlatanova et al., 2016).

Zlatanova et al (2016) investigate the synergies between LADM and IndoorGML. After the study of both models, they highlighted a straightforward equivalence of two classes, that is, CellSpace of IndoorGML and LA_SpatialUnit of LADM. CellSpace is a base class of IndoorGML for representing the indoor space describing it through a 2D or 3D geometry, which supports the abovementioned claim of the authors. Although these classes are defined for different purposes they can be externally associated (Figure 25). Through this link a LADM extension of IndoorGML can be created. Also, other researchers proposed the integration between LADM and IndoorGML following the same norm.

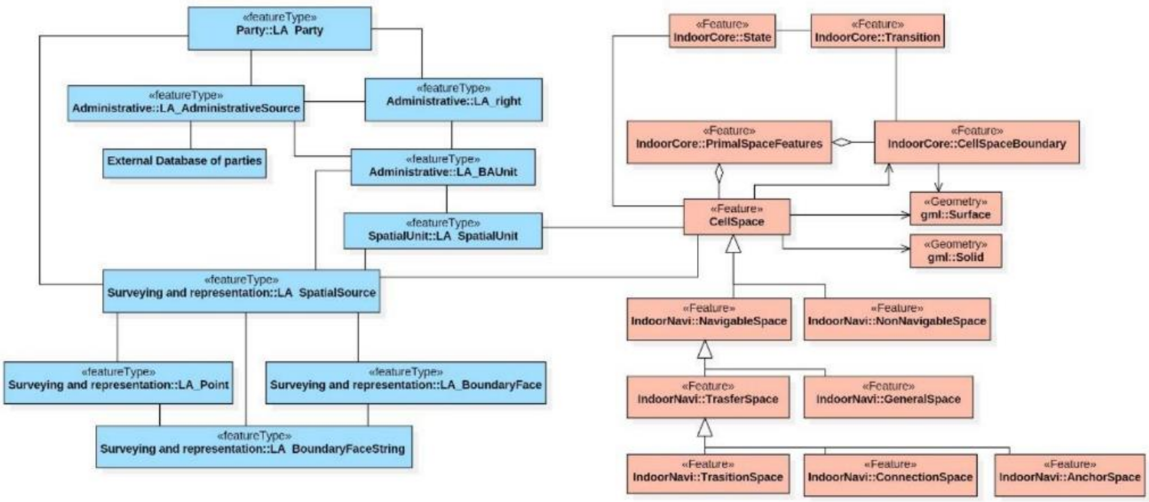


Figure 26. The integrated model of LADM (blue) and IndoorGML (red) (Source: Alattas et al. 2017).

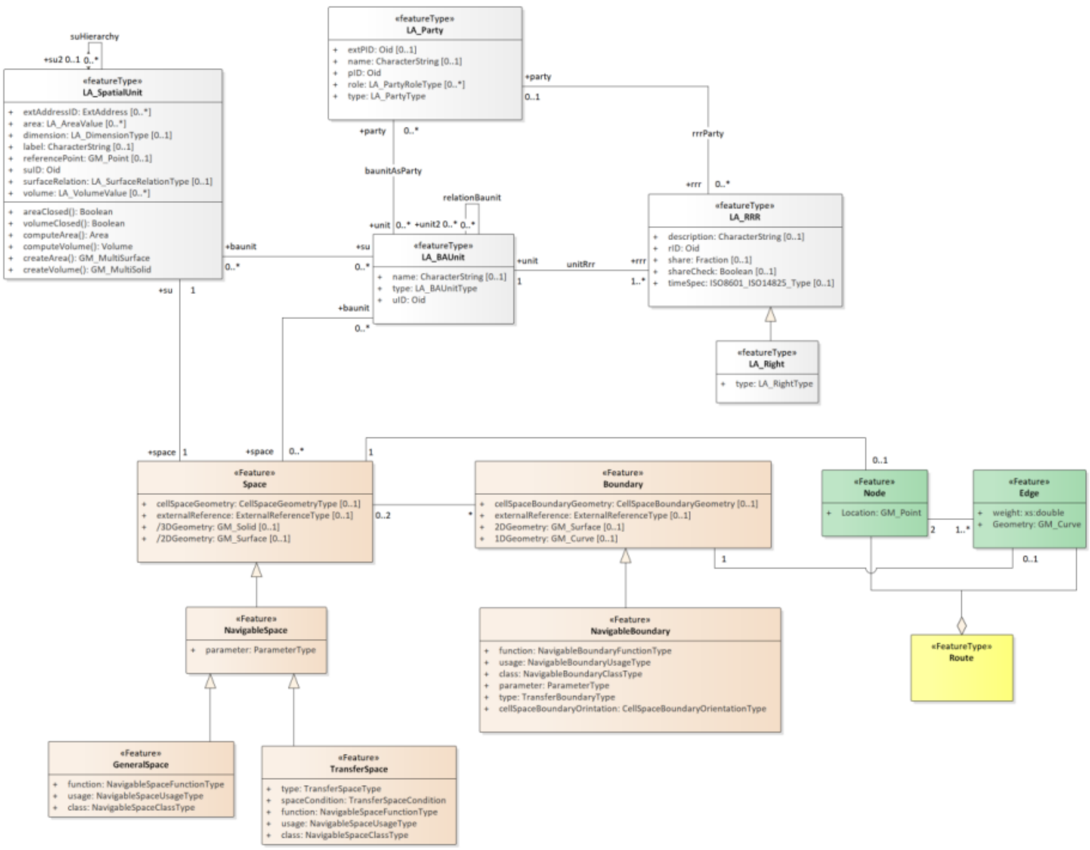


Figure 27. The selected classes from the conceptual model of LADM-IndoorGML (Source: Alattas et al. 2018b).

Alattas et al. (2017) investigated the combination of LADM and IndoorGML for the purpose of indoor accessibility predicated on RRR information. Based on the RRR information that is available to the users, the last ones can avoid inaccessible areas. The implementation of the combined LADM-IndoorGML model for two university buildings demonstrated the validity of the suggested strategy for assisting an RRR-based indoor navigation in a practical setting. Alattas et al. (2017) proposed to associate LADM with IndoorGML by linking the two standards through the CellSpace class in IndoorGML and the LA_SpatialUnit in LADM in order to define the accessibility for the user based on their right (Figure 26).

Recently, the problems and difficulties in translating the conceptual LADM-IndoorGML model into a technical implementation were further investigated. Incorrect handling of primary and foreign keys, associations, cardinality of multiplicity, geographic and non-spatial data types, spatial data indexing, restrictions, and inheritance were the main transformation difficulties (Alattas et al., 2018a). To solve these problems, Alattas et al. (2018b) proposed and created a database for the LADM-IndoorGML model, allowing queries to get accessible and inaccessible interior places based on RRR data (Figure 27). At a later stage, the LADM-IndoorGML model was also used and tetsed for evacuation purposes in complex buildings structures (Alattas et al., 2018c).

Linking LADM and IndoorGML standards is still on a conceptual level (Tekavec and Lisec, 2020). Nevertheless, the ongoing investigation may lay the foundation for the future indoor navigation systems integrated with RRR information.

2.4.3 LandXML

To facilitate digital management of land and infrastructure facilities such roads, trains, tunnels, surveys, alignments, land division, and condominium units, the Land and Infrastructure (LandInfra) conceptual standard was recently created (Scarponcini et al., 2016). LandInfra concepts were implemented using a GML-based encoding called InfraGML. The legal concepts defined in LandInfra are in line with a subset of the LADM standard. However, LandInfra does not consider the specific classes of party package the same way as defined in LADM. The RRR information is modelled by the InterestInLand class in LandInfr, while the geometric modelling of spatial units is independent from the legal ownership of these units. As a result, LandInfra places more of an emphasis on cadastral surveying and infrastructure than it does on the legal and administrative facets of property development.

Thompson et al. (2016) explores an integrated method of defining 3D spatial units through an alternative approach of the combined use of LA_BoundaryFaceString and LA_BoundaryFace within the LandXML encoding structure. More specifically, the “footprint” of the spatial unit may be represented as a LA_BoundaryFaceString, associated with a - possibly empty - set of more general faces (LA_BoundaryFace) (Figure 28). Although a spatial unit may be defined by a bounded space by five or more vertical faces of undefined height, the database representation only need a simple polygon. Based on this and the observation that the majority of 3D parcels are relatively simple consisting of vertical and horizontal faces, an alternative and simplified definition of 3D spatial units based on the 2D footprints is investigated. This representation fits within the LADM, is suitable for practical encoding formats and is more parsimonious in storage than the conventional polyhedron.

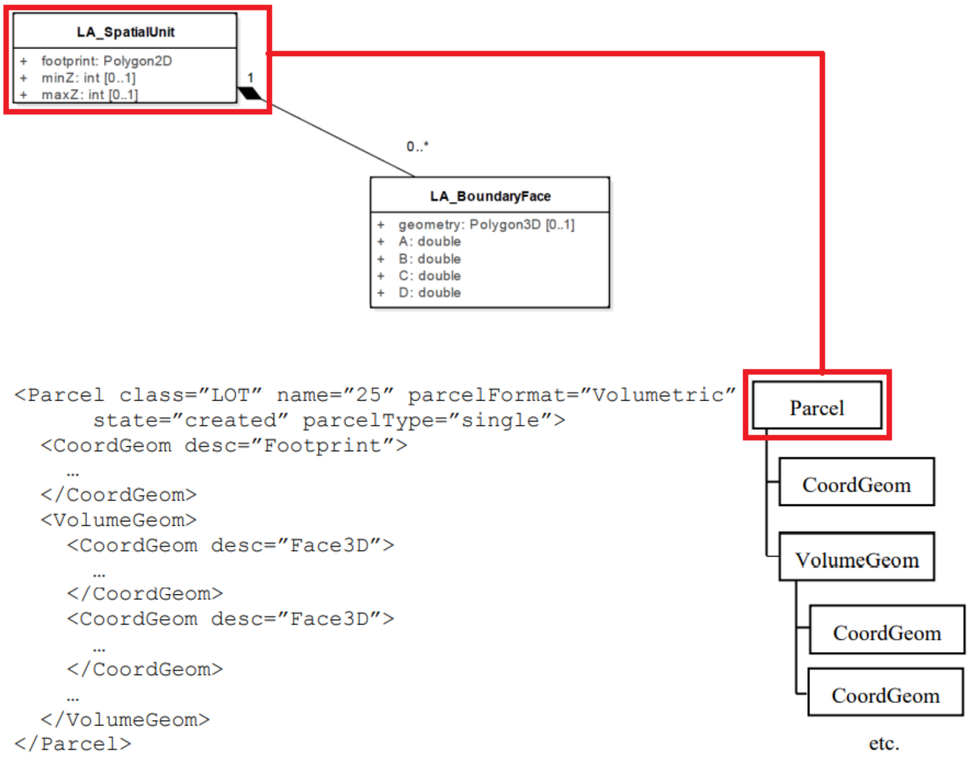


Figure 28. Potential link between a Simplified schema for database storage and the Simple Faces Method for encoding of a 3D Spatial Unit (Source: Thompson et al., 2016).

The need for harmonizing LandInfra and LADM standards in the field of land administration was emphasized by Stubkjr et al. (2018). In order to allow semantic harmonization of concepts between LADM and LandInfra and to mitigate interoperability concerns in the land administration sector, cross-standard management of code lists was explicitly recommended. LandInfra has more detailed code lists than LADM, in order to facilitate semantic management of condominium units (Çağdaş et al., 2018). These code lists include condominiumMainPart, condominiumAccessoryPart, jointAccessFacility, and jointOtherFacility. However, in LADM, there is only the LA_BuildingUnitType code list that includes generic shared and individual values (Çağdaş et al., 2018).

2.4.4 BIM/IFC

BIM provides a valuable tool that is rich in content and able to provide input to a 3D cadaster, both for each property unit itself and for its surrounding property units and parcels. The BIM can be translated in BuildingSMART's open exchange standard, IFC, which provides the capability to model the legal and physical dimensions of urban properties (Barzegar et al., 2021). A properly enriched IFC model may satisfy the requirements of cadastral legal spaces, enabling the extraction of cadastral data from both as-designed and as-built BIMs (Oldfield et al., 2016). Oldfield et al. (2016) investigated the potential adoption of existing 3D data sources, as 3D Building Information Models (BIMs), in 3D cadastre. They described how IFC entities can be used to model some concepts from LADM. In particular, they stated that 'ifcSpace' and 'ifcZones' entities may be a good fit for modelling spatial units. A 3D spatial unit such as a building unit may be represented as a closed polyhedron that can be mapped to an 'IfcSpace' object. This space object is enclosed by several polygonal faces illustrating a conceptual mass (Figure 29).

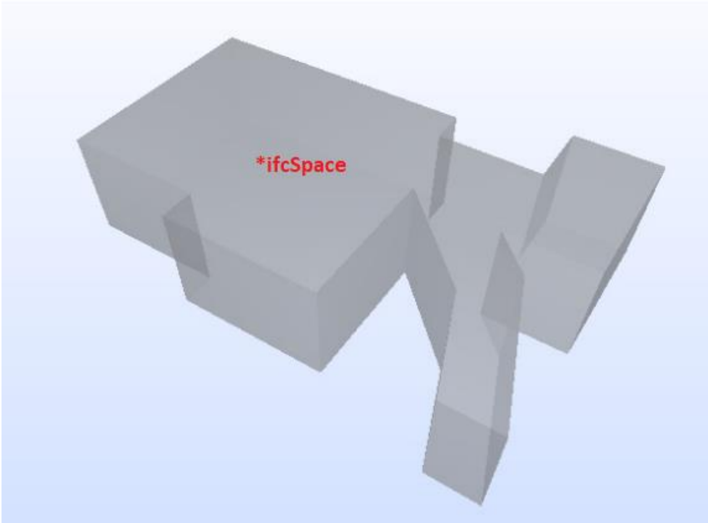


Figure 29. Conceptual Mass as 'IfcSpace' object (Source: Oldfield et al., 2016).

To enhance this notion, Oldfield et al. (2017) designed a workflow to establish a bridge between a BIM and LADM through developing an extended IFC data structure able to incorporate the information on 3D RRRs as the input for the land registry of The Netherlands (Figure 30). Also, they recognized the use of property sets for managing legal information but without proposing how various property sets based on LADM may be applied to different IFC entities (Figure 31).

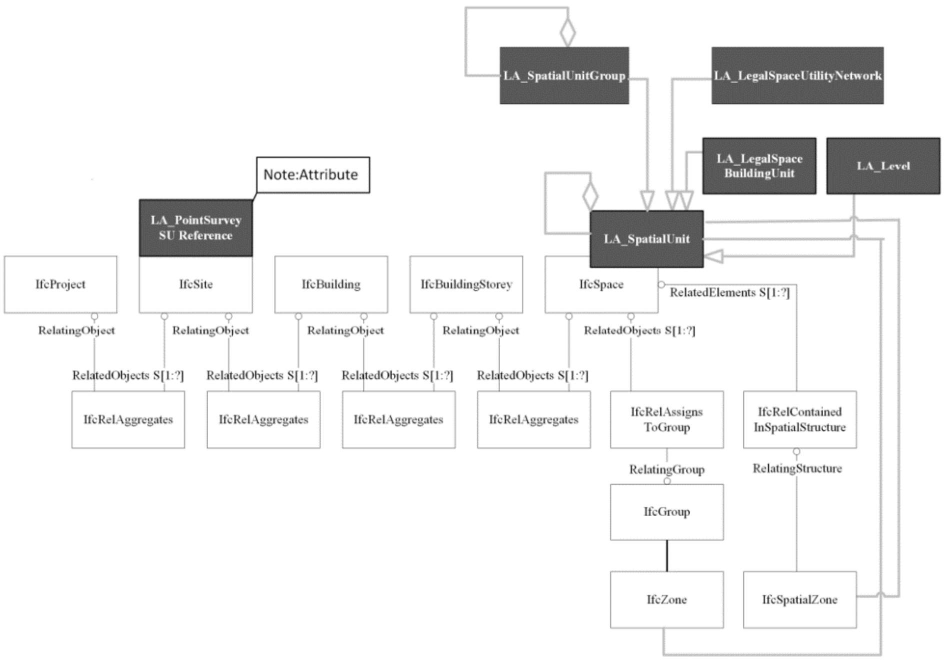


Figure 30. Mapping between the LADM and the IFC:Decomposition (Source: Oldfield et al., 2017).

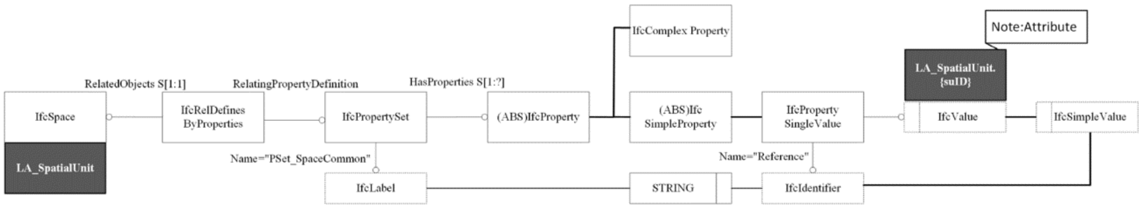


Figure 31. Mapping between the LADM and the IFC:Properties (Source: Oldfield et al., 2017).

Form of spatial unit		**Suitable IFC entities**
Land parcel	Individual	IfcSite
	Multiple	IfcSpatialZone
Indoor legal space	Individual	IfcSpace
	Multiple	IfcZone, IfcSpatialZone
Outdoor legal space	Individual	IfcExternalSpatialElement
	Multiple	IfcSpatialZone

Figure 32. Suitable IFC entities for modelling spatial units (Source: Atazadeh et al., 2018).

Atazadeh et al. (2018) investigate two potential approaches to integrating physical information provided through the IFC standard and legal information provided by the LADM data model. The first approach describes how the IFC standard may be extended to the land administration domain, while the second approach proposes the incorporation of physical elements from the IFC standard into a potential future update of the LADM. As for the first approach, they consider two main representation forms, a 2D for the land parcel and a 3D for the legal spaces. They proposed a potential matching between the IFC entities and the spatial units in order to model them. The selected IFC entities are presented in the Figure 32. Furthermore, for the second approach they suggest a potential consideration of physical objects in LADM standard and define their optional relationships with the legal objects. Their proposal is based on physical objects defined in IFC standard (Figure 33).

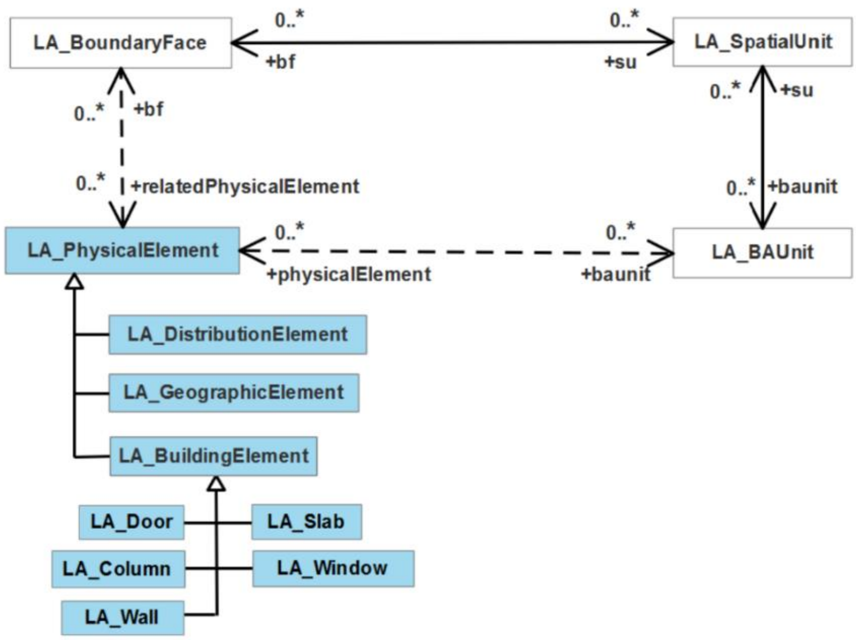


Figure *33*. Proposed physical concepts for LADM (Source: Atazadeh et al., 2018).

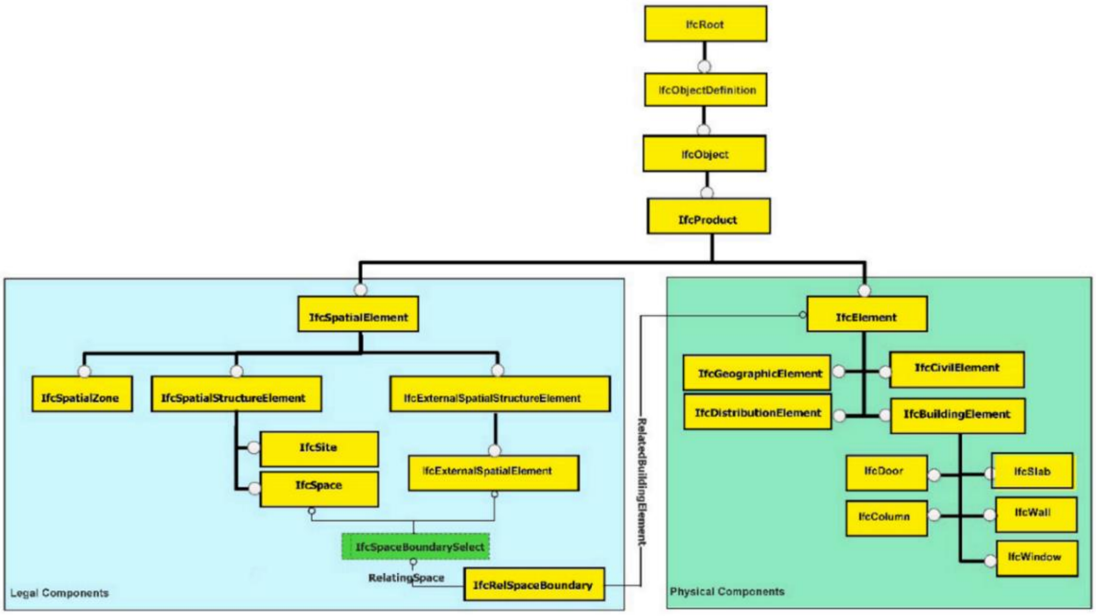


Figure 34. Different sections of the IFC standard used for modelling legal and physical components (Source: Atazadeh et al., 2021).

Atazadeh et al. (2021) proposed using the IFC schema to model the features and attributes in LADM. In summary, the subclasses of IfcSpatialElement are suggested as suitable classes for modelling legal components. These subclasses are IfcSpatialZone, IfcSpace, IfcSite, and IfcExternalSpatialElement. The physical components in IFC are defined as subclasses of IfcElement class. These subclasses include IfcBuildingElement (and its subclasses including IfcWall, IfcDoor, IfcWindow, IfcSlab), IfcDistributionElement, IfcGeographicElement, and IfcCivilElement. Figure 34 shows different sections of the IFC standard, in which the legal and physical components are highlighted.

Guler and Yomralioglu (2021) demonstrate how condominium rights in the buildings in Turkey can be represented using the initial conceptual model containing IFC and LADM. However, the model in this study contains only a part of LADM classes without considering the building elements and linking these classes to suitable IFC entities. In a subsequent investigation Guler et al. (2022), provide a model that extends IFC schema by referencing LADM in the sense of re-using BIM/IFC model for the 3D registration of condominium rights in Turkey. Following a similar reasoning with Gürsoy Sürmeneli et al. (2022a; b), the mapping between BIM/IFC and LADM classes was created. Figure 35 (left) illustrated the Party and Administrative packages while Figure 35 (right) presents the Spatial package and the Surveying and Representation sub-package of the integrated model.

Figure 35. Party and Administrative packages (left); Surveying and Representation sub-package (right) of the integrated LADM-based Turkish model (Source: Guler and Yomralioglu, 2021).

2.5 Conclusions

The rapid economic, digital and social transformation through the last several years, has led to multiple rearrangements regarding the land administration procedures. The development of large cities, especially in developing countries, and the phenomenon of megacities are a reality that imposes the necessity of recording 3D geoinformation and the creation of 3D cadastral. It is recognized that the current cadastral systems, based on two-dimensional cadastral maps, may not be efficient enough to visualize the exact legal and physical boundaries of the 3D property units to which property rights may refer in complex urban areas in the near future, and therefore may not be reliable for supporting urban activities. The sustainable management of large and mega cities requires transparency and credibility in the determination of property rights at every level, bringing the 3D cadastre into the spotlight. 3D cadastre has been attracting researchers throughout the world for nearly a decade, bringing in line very interesting approaches describing how 2D cadastral systems should best be transformed into 3D cadastres. However, the implementation of a fully functional 3D cadastre has not been achieved yet, as in addition to the determination of the technical specifications concerning the geometric determination of the legal and physical spaces, radical changes are also required in the current legislation of each country.

With the emergence of the LADM in 2012, a new era has begun for both 2D and 3D cadasters. Based on this ISO standard, many countries have/can design prototype systems and approaches for the implementation of country-level 3D cadasters. Each country handles the 3D aspect according to its current legislation and cadastral background. The LADM has become a very useful tool as it provides a flexible conceptual schema as a basis for the development of 2D and 3D cadasters while establishing a shared ontology, enabling communication between the involved parties within one country or between different countries, and facilitating data exchange in heterogeneous and distributed land administration environments.

Despite LADM provides an internationally accepted standard structuring the legal relationships between interest holders and their land or property, it lacks a determination regarding the acceptable 3D geometries and representations of 3D cadastral objects, consisting a subject of active research. Besides that, another weakness of the LADM is the absence of a connection with widely known spatial models. Existing research projects investigated various methods for developing an integrated legal-physical 3D data model. Several different integrations of physical models, such as CityGML, IndoorGML and BIM/IFC, and legal models, such as LADM, have been considered in these investigations. Especially, the BIM provides a valuable tool that is rich in content and able to provide significant input to 3D Cadastres, both for each property unit itself as well as for its surrounding property units and parcels. The BIM can be translated in BuildingSMART's open exchange standard, IFC, which provides the capability to model the legal and physical dimensions of urban properties. A properly enriched IFC model may satisfy the requirements of cadastral legal spaces, enabling the extraction of cadastral data from both as-designed and as-built BIMs. However, the investigation on the interaction between IFC and LADM standards to construct an integrated model is still narrowed. As a suggested future pathway for designing an integrated 3D cadastral data model were either encoding LADM concepts inside international data models such as IFC, CityGML, IndoorGML etc., or expanding future versions of LADM standard by incorporating physical concepts from these widely used data models.

Nowadays, such rich data models are utilized in several application areas with great efficiency and have become a valuable data source for Geographic Information Systems (GIS), such as 3D cadastral systems. However, their availability remains limited, failing to cover all possible implementations. Nevertheless, in recent literature numerous other 3D data sources are appeared, capable to describe the 3D aspect of the cadastral objects including lidar data, aerial, terrestrial or space-borne optical data, topographical data, terrestrial laser surveys, and data derived from crowdsourcing or volunteered geographic information (VGI), which may be further investigated.

Chapter 3

Extraction and modelling of 3D geospatial data

In recent years, technological advances have made possible the development of more and more innovative and effective tools for acquiring accurate and reliable 2D and 3D data, as well as their efficient processing in terms of automation, speed and data quality. Buildings, consist the most significant place for human livelihood, possessing a key role on digital mapping of urban and suburban areas. Detection, extraction and 3D reconstruction of man-made objects, especially buildings, is an intensive and long-lasting research problem in the graphic, computer vision and photogrammetric communities. 3D digital buildings models are required in many applications such as inspection, navigation, object identification, urban planning, GIS, tax assessment, cadastre, insurance, 3D city modelling, digital twins, etc. The most common requested specifications for such applications include high geometric accuracy, photo-realism of the final results, modelling of the complete details, as well as automation, low-cost, portability and flexibility of the modelling techniques. Therefore, selecting the most appropriate 3D data acquisition and reconstruction method is not always an easy task. It depends on many parameters, including the scale, the type of the scene as well as the available funding.

Regarding 3D Cadastre where the needs for 3D models are high and their availability is limited, the automation in detecting, extracting and reconstructing building units can be a great contribution, especially in cases of areas with insufficient geospatial infrastructure. Today, the increasing quality of digital airborne cameras as well as the recent innovations in matching algorithms, allow the generation and disposal of high-resolution imagery, the computation of dense 3D point clouds and the generation of DSMs sufficient to assist the reconstruction procedure. Simultaneously, the remarkable progress in the field of computer vision (CV), indicates that in addition to traditional photogrammetric techniques, deep learning techniques may essentially improve the performance of object detection and semantic segmentation, playing a critical role in promoting the accuracy of buildings detection towards applications of automatic mapping.

This chapter provides a comprehensive overview of 3D reconstruction algorithms and techniques that generate 3D models from different data sources. The main focus is on man-made scenes, specifically buildings, and how the described methods and techniques can be leveraged to support 3D Cadastre. First, a classification of the different 3D data acquisition methods and the most common 3D input data required by the majority of reconstruction methods, is presented. Then, an extensive literature review of the state-of-the-art 3D reconstruction methods, techniques and algorithms, concerning the 3D reconstruction of buildings, is made.

Following, the investigation focuses on the exploitation of high-resolution geo-referenced aerial imagery, for the detection, extraction and potential reconstruction of buildings either in sparsely or in densely urbanized areas. Section 3.3.1 focuses on the automated detection, extraction and reconstruction of noisy buildings' roof tops in densely urbanized areas, using photogrammetric techniques. The processing steps of developed methodology are described and each stage of the proposed methodology is analyzed. The developed software is presented and an implementation of the proposed procedure is conducted. Then, an assessment of the produced data and a comparison with the results of other software is made. Section 3.3.2, focuses on the automated detection, extraction and vectorization of buildings outlines in sparsely urbanized areas, using deep learning. First, the main stages of the developed methodology are described and the main characteristics of the developed cloud-based software are presented. Next, a practical experiment of the developed methodology is presented and the first results are evaluated. Finally, the potential integration of these methods in 3D cadastral processes is discussed and the main conclusions referring to the work presented in this Chapter are introduced.

3.1 Data Acquisition

This section discusses the different methods for data acquisition, which are often used for reconstructing man-made objects and scenes. First the data acquisition methods are classified and then the most common data used as input for the generation of 3D reconstructions, are categorized and presented.

The most general classification of data acquisition techniques divides them into *contact* and *non-contact* methods (Figure 36). *Contact* methods refer to coordinate measuring machines, calipers, rulers and/or bearings while *non-contact* methods refer to remote sensing techniques such as photogrammetry, SAR (Synthetic Aperture Radar), LIDAR (LIght Detection and Ranging) and laser scanning. Nowadays the generation of 3D models is mainly achieved using *non-contact* methods based on light waves. These methods are distinguished in *active* and *passive* methods (Remondino & EL-Hakim, 2006) (Figure 36). *Active* methods control the light sources, as part of the strategy to arrive at the 3D information. Active lighting incorporates some form of temporal or spatial modulation of the illumination. On the other hand, *passive* methods control the light sources only with regard to image quality. Usually *passive* techniques, such as photogrammetry, work with sufficient ambient light available. While *passive* photogrammetric techniques provide a cost-efficient method for different scales, *active* methods such as laser scanning, tend to be less demanding, as the special illumination simplifies some steps in 3D capturing process. However, their applicability is restricted to environments where the special illumination techniques can be applied (Moons et al., 2010).

A subsequent distinction is between the number of viewpoints from where the scene is observed and/or captured. Therefore, there are the *single-view* and the *multi-view* methods (Figure 36). In case of 3D models *multi-view* methods are usually selected. For multi-view methods to work well, the different components often have to be positioned far enough from each other regarding a specified baseline. The latter ones generate multiple registered 2D images and/or a point cloud of the measured 3D scene (Moons et al., 2010). With photogrammetric techniques the viewpoints of multiple input photos are estimated and additionally a sparse or dense point cloud of the scene is generated. With laser scanners and range cameras a dense point cloud of a scene is directly created. These 3D data consist the core pillar of 3D reconstruction, which is the Digital Elevation Model (DEM) generation.

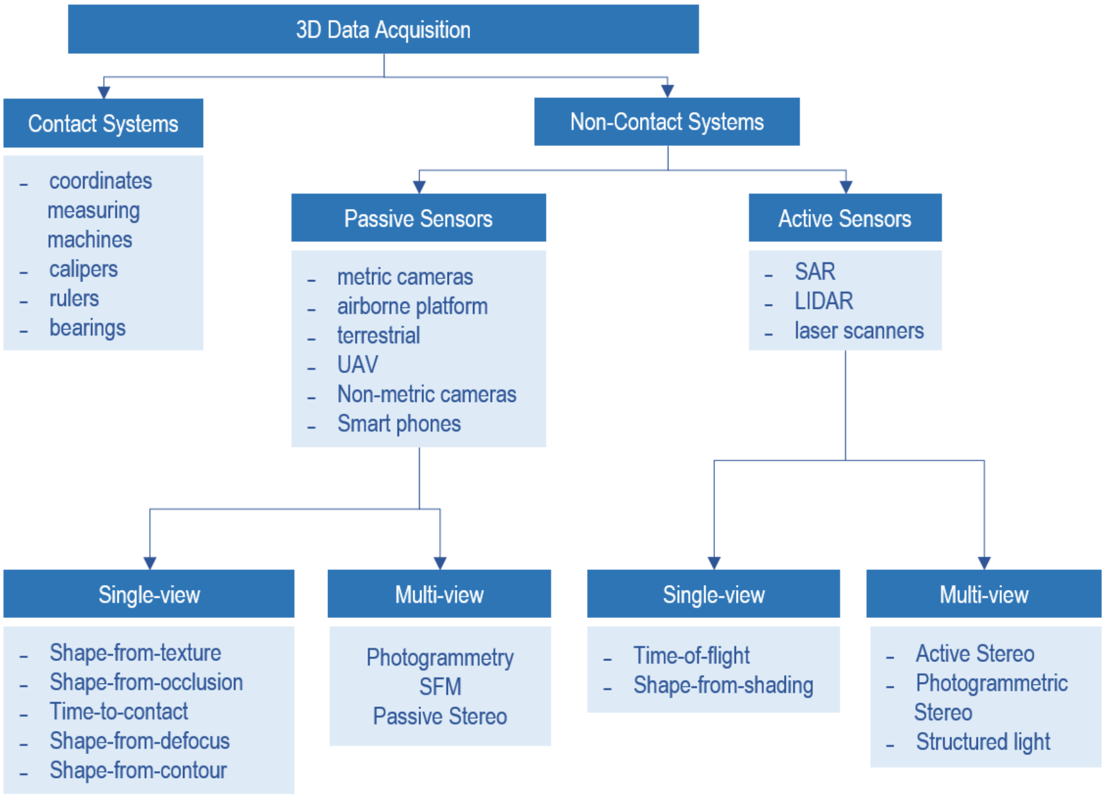


Figure 36. Three-dimensional acquisition systems for object measurement using non-contact methods based on light waves.

3.1.1 3D Input Data

Current reconstruction methods have different types of input requirements. The most common input is a set of 3D points that samples surface of the object. However, working only with point clouds may fail to sufficiently deal with the inconsistences existed in the point clouds. Thus, other types of input data may be considered as extremely beneficial in such reconstruction processes. Considering active and passive sensors, four alternative data sources for 3D reconstruction can currently be distinguished:

- *Passive sensors and 2D images*. This approach is widely used for precise terrain and city modelling (Grun, 2000) utilizing 2D image measurements (correspondences) to recover 3D object information. Passive sensors acquire 3D measurements from multiple views (aerial or terrestrial imagery), through the use of projective geometry (Nister, 2004; Pollefeys et al., 2004) or a perspective camera model. Aerial imagery can either be captured with the use of an airborne platform with specially manned aircraft or with Unmanned Aerial Vehicles (UAVs). Although these images are generally captured with metric cameras, the recent technological achievements allow the use of conventional non-metering cameras. The use of UAVs with conventional non-metric cameras has been attracting particular interest lately. Also, recent developments in smart devices (e.g., smartphones), which have built-in positioning sensors (e.g., Global Navigation Satellite System (GNSS) receiver, Inertial Measurement Unit - IMU) and a camera for taking photos, offer the possibility of utilizing more information in photogrammetric reconstruction process, so that it is possible to increase the computational efficiency, reliability and accuracy of the process (Zhang et al., 2016). Therefore, the images required for photogrammetric reconstruction procedures can be also obtained with low cost devices and by people without photogrammetric skills (e.g. through crowdsourcing techniques) reducing the costs of the overall procedure. Hence, toward all these alternatives seems that image-based modelling approaches are portable and the sensors are often low cost.

The utilization of such data in 3D reconstruction procedures presupposes the restoration of 3D information from one or more images that is mainly achieved through photogrammetric techniques. The first step of the photogrammetric procedure involves the orientation of all the input images. This problem has preoccupied the research community for many decades as significant efforts have been made to automate the required procedures. These techniques have now matured, resulting in their increasing use in large-scale industrial and non-industrial applications. Among several orientation strategies (Westoby et al., 2012; Weng et al., 2012; Mayer, 2014; Mayer, 2015; Nguatem et al, 2016; Verykokou & Ioannidis, 2016) the most common is Structure-From-Motion (SFM) algorithm that enables the computation of the intrinsic and extrinsic camera parameters (Hartley & Zisserman, 2003). This process is widely known as sparse matching and it is differentiated from dense matching which aims to find a complete solution and create a dense and qualitative model of a 3D scene. Unlike conventional photogrammetric methods and LIDAR systems or terrestrial scanners that capture directly the 3D geometry of the object or scene, dense matching methods provide economy, speed, and greater reliability. The latter is due to the fact that together with the final 3D information, the results are accompanied by qualitative - radiometric information, which are extracted from the input images. Dense image matching can be performed using several methods, which are combinations or variations of the two main categories. Each of them has advantages and disadvantages, depending on the required quality of the final result (Scharstein & Szeliski, 2002). The main categories of methods are summarized into: (i) local and (ii) global methods. The most known dense image matching algorithms are the Semi-Global Matching (SGM) algorithm (Hirschmüller, 2005; 2007; 2011; 2012; Hirschmuller & Scharstein, 2007; 2008) and Multi View Stereo (MVS) algorithms (Furukawa & Hernández, 2015). Multi-view stereo algorithms are designed to manage a very large number of images and compute dense point clouds or triangulated meshes from the input data. As input, aerial images and terrestrial images may be utilized. The use of both of these image categories is necessary in order to fully describe all aspects of each object or scene, and to prevent problematic situations (e.g. hidden areas) introducing errors in the process.

- *Active sensors and 3D Point Clouds*.

  In the past years many advances have been made in electronics and photonics resulting to the development of a wide variety of active 3D sensors (Blais, 2004) provide a highly detailed and accurate representation of the object or scene. However, these systems are very expensive consisting a costly solution to proceed with 3D reconstruction. Nowadays there are many commercial solutions, based on triangulation, time-of-flight, continuous wave, interferometry or reflectivity measurement principles (Remondino et al., 2006). These solutions are becoming very popular as they enable non-experts to participate to the overall process.

  Most of the systems focus only on the acquisition of the 3D geometry of the studied object or scene, providing only a monochrome intensity value for each range value. Some systems directly acquire color information for each pixel (Blais, 2004) while others have a color camera attached with a known configuration, allowing them to acquire texture registered with the captured geometry. One of the most common sensors belonging in this category is LIDAR. In addition, another type of an active sensor is the INSAR (Interferometric Synthetic Aperture Radar). Both systems can be used to develop applications for detection and consequently, reconstruction of buildings. However, LIDAR systems have a key advantage over INSARs in terms of spatial analysis and the ability to capture vertical data.

- *Combination of different data sources*.

Usually, reconstruction algorithms which use only 2D images as input data, introduce several limitations and complicate the whole reconstruction process. This setback is due to the existence of misleading and low level of information or even lack of information or noise (Karantzalos & Paragios, 2010). Thus, in some cases is preferable to combine data from different sources to increase the reliability of the final model. Ordinarily, the basic geometric shapes such as planes are derived by image-based methods while the rest fine details are employed by range sensors (Flack et al., 2001; Sequeira et al., 2000; Bernardini et al., 2002; Borg & Cannataci, 2002; El-Hakim et al., 2004; Beraldin et al., 2005). In some applications, other information derived from CAD (computer-aided design) models, measured surveys, Global Positioning System (GPS) and Crowdsourcing may also be used and integrated with the sensor data.

3.2 3D Reconstruction Algorithms and Techniques

Over the last twenty years, the automatic extraction and reconstruction of 3D buildings has been a major research focus, trying to replace the manual reconstruction of buildings from aerial imagery via stereoscopy or from LiDAR data, which are time consuming and laborious tasks. In order to achieve full automation, aerial imagery and LiDAR data need to be used in synergy in order to utilize their superior positional and height resolutions respectively (Brenner, 2005). Recent advances in computer vision technology, the increasing quality of digital airborne cameras as well as the recent innovations in matching algorithms, have already demonstrated digital image matching as a valid alternative to airborne LiDAR. Therefore, the computation of dense 3D point clouds and the generation of Digital Surface Model (DSM) with surface resolution similar to the ground sampling distance of the available imagery, is feasible. 3D point clouds and DSMs, are of fundamental importance for 3D reconstruction of real-world, as they guide the overall reconstruction process, providing information about the studied surface. However, automatic building extraction and reconstruction from remote sensing images are difficult tasks, as the detection accuracy and the quality of the produced surface, depends heavily on image resolution, quality and buildings shapes (Köhn et al., 2016).

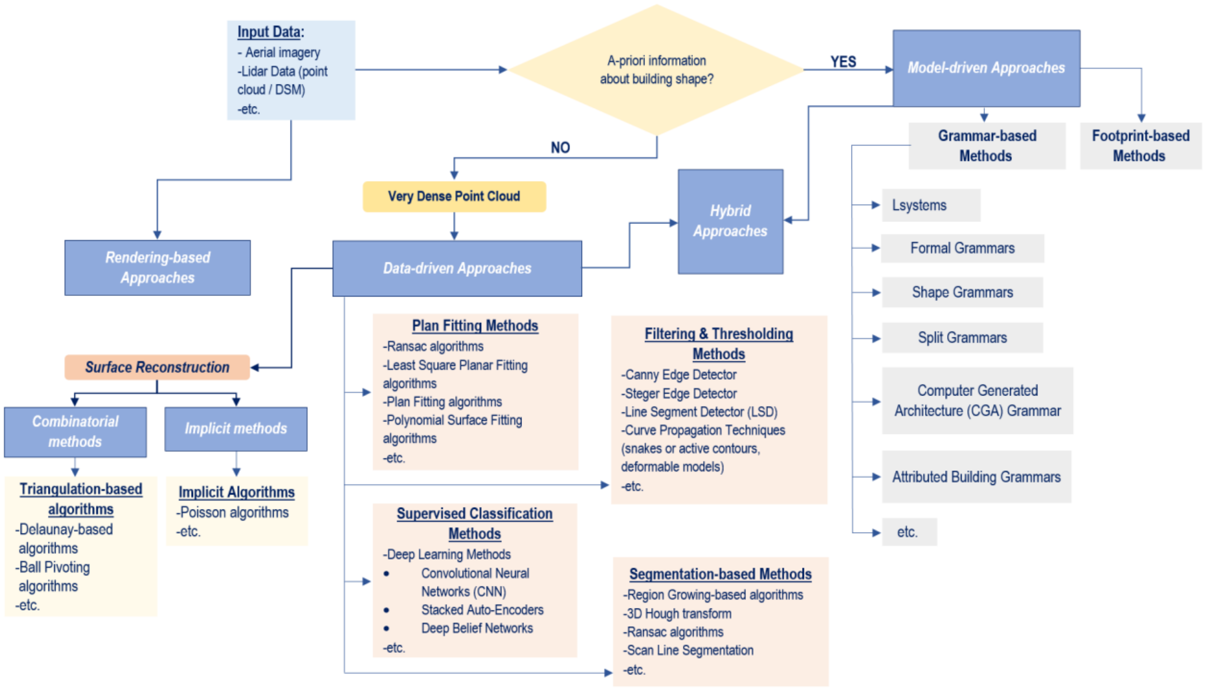


Figure 37. Classification of 3D reconstruction methods.

In recent literature several methods have been developed for the automatic building detection, recognition and reconstruction. These methods can be divided into three general categories based on the degree of the contextual knowledge: (i) Model-driven methods, (ii) Data-driven methods, and (iii) Hybrid methods. For the data-driven methods, buildings are usually considered representing the aggregation of roof planes represented by the blocks of point clouds or the DSMs. Some of these techniques may not produce a surface representation, but rather a resampled optimized point set, free from noisy artifacts and non-building elements. Once the point cloud representing building's structure parts is defined through the abovementioned methods, the respective surface has to be reconstructed. Through numerous approaches, surface reconstruction methods can be divided into two (2) broad categories: (a) combinatorial algorithms and (b) implicit functions. Each one of these methods include several algorithms and techniques aiming to achieve a successful 3D building reconstruction (Figure 37).

3.2.1 Rendering-based methods

Rendering methods are preferable in cases where high precision is not required and the study scale of the object or scene is not very large. These approaches do not lead to the generation of a 3D model but, for particular objects and under specific camera motions and scene conditions, it might provide a good solution for the generation of virtual views (Shum & Kang, 2000). However, the final outcome may be affected by current occlusions and discontinuities that usually encountered in large-scale and geometrically complex environments. Hence, the utilization of these approaches is limited to specific applications. As initial data, a particularly dense point cloud is required. Therefore, the reconstruction can be done through rendering color at each point of the point cloud. The final outcome may be presented as a visually complete surface, but in fact it consisted by a set of individual unrelated points.

Xua et al., (2016), proposed a rendering-based approach for the 3D reconstruction of cultural heritage objects. In order to collect detailed information regarding the buildings' rooftops and facades, investigates the potential integration of data from UAVs and terrestrial laser scanners (TLS). Instead of images, UAV video recording is selected in order to tackle with the limitation of static shooting, which is introduced through capturing images at specific times. A point cloud is generated through the SFM and the Patch-based Multi View Stereo (PMVS) (Furukawa & Ponce, 2009) algorithms, utilizing video frames. After the integration of the two-point clouds into the same system, the corresponding tone is rendered at each point providing the final digital 3D reconstruction with full coverage and texture information.

3.2.2 Model-driven methods

Parametric methods or top-down approaches are based on a priori known information about the shape of the buildings. A library of parametric shapes consists of a set of predefined patterns, which are described by a number of parameters. An appropriate combination of these parameters is needed, in order to evaluate the best 3D model. The main advantages of parametric methods are the robustness in the case where the initial data are incomplete and weak, and the topologically correct model output (Sohn & Dowman, 2007; Wichmann et al., 2015). However, each library may not include enough information about all kinds of buildings geometry. Thus, in case of buildings with complex shapes the reconstruction may not be complete.

One of the most popular categories of parametric methods are *Grammar-based* methods. *Grammar-based* methods have been extensively used in architecture modelling. These methods are supported by a structure, called Grammar and use a language named L(GB), that includes several different shapes and attributes which may constitute potential components of the building structure (Grammar Building). Based on GB, a segmentation process starts, where every component is checked against a set of rules. The main objective of this process is to categorize the initial data and find all the terminal elements that constitute the studied object. In case of buildings, the doors, windows, walls, etc., may be considered as such elements that may cannot undergo a further segmentation. Essentially, the Grammar (GB) consists of four distinct elements GB = [T, N, R, I], where T is the terminal element (cannot further segmented), N is the non-terminal element (can be further segmented into other terminal or non-terminal elements), R is the set of rules followed during the segmentation (e.g. if a building is symmetric, one part of the building is created and then the second part is adapted; or, if there are similar primitives, the first one is generated and then the rest are replaced), and finally I represent the initial element. Thus, having an initial dataset (e.g. point cloud) the segmentation process begins, aiming to categorize the initial data and find all the terminal elements that constitute the studied object.

The most well-known examples of *Grammar-based* methods are Lsystems (Lindenmayer-systems), Shape Grammars, Split Grammar, Computer Generated Architecture (CGA) Grammar, Formal Grammars and Attributed Building Grammar (Yu et al., 2014). Lsystems, were developed for modelling plants, so they are not appropriate for the modelling of individual buildings and thus will not be further investigated. On the contrary, Shape grammars include shape rules and a generation engine that selects and processes the rules. The shape rules define how an existing shape can be transformed. The shape grammars have been successfully used in architecture (McKay et al., 2012); however, their applicability for automatic generation of buildings is limited. Karantzalos & Paragios (2010) proposed a different approach, which utilizes the methodology of Shape Grammars. The proposed method refers to a Grammar, which is composed of a three-dimensional (3D) shape priors. According to this methodology, the choice of the most suitable model is via the optimal selection of parameters which form the shape of the building part.

Wonka et al. (2003) employed a *split grammar* to generate architectural structures based on a large database of split grammar rules and attributes. In this approach, a split grammar is introduced for dividing the building into parts, and also a separate control grammar is proposed to handle the propagation and distribution of the attributes. However, due to the requirement of an excessive amount of splits for complex models, the proposed split grammars have limitations to handle the complexity of architectural details. Following this idea, a new *Computer-Generated Architecture (CGA) grammar* is presented by Müller et al. (2006) to generate detailed building architecture in a predefined style, which is demonstrated by a virtual reconstruction of the ancient Pompeii. They solely use context-sensitive shape rules to implement splits along the main axes of the facades.

More recently, *formal grammars* have been applied in building facade modelling (Becker & Haala, 2009) to reconstruct building facades from point cloud data. Depending on the structures of facade, the façade model is defined by a formal grammar. Each grammar rule subdivides a part of the facade into smaller parts according to the layout of the facade. However, facade modelling does not consider the entire building and is limited to certain type of structures in some cases, e.g., symmetric structures. Yu et al. (2014) proposed an automated reconstruction method in order to provide 3D building models from segmented data based on *pre-defined formal grammar* and rules. Terrestrial or mobile laser scanning devices are utilized for the acquisition of the initial data, which then undergo through segmentation procedures. The main objective is to extract the original shapes, which with the help of Formal Grammar and the corresponding rules, will lead to the generation of the desired model. The proposed methodology is distinguished by two main steps. The first step concerns the transformation of the segmented data into 3D shapes, for instance using the DXF (Drawing Exchange Format)

format which is a CAD data file format used for data interchange between AutoCAD and other program. Secondly, a formal grammar is developed aiming to describe the building model structure and integrate the pre-defined grammars into the reconstruction process. Based on the different segmented data, the selected grammar and rules are applied to drive the reconstruction process in an automatic manner. Compared with other similar approaches, this method allows the model reconstruction directly from 3D shapes and examine directly the whole building.

The next years, Yu et al., (2016) proposed another automated method of reconstruction of buildings using an *Attributed Building Grammar*, which starts with the segmentation of the initial point cloud in order to extract planar, cylindrical, and other types of surfaces, by methods such as PCA (Principal Component Analysis). The segmented data transformed into 3D shapes which represent the 3D building structures. Subsequently a Grammar engine, lead the reconstruction process, ensuring the enforcement of appropriate rules, for the further subdivision into elementary shape structures. The division is described by a tree structure, wherein the body represents each shape and the leaves represents the elementary objects. Finally, the 3D model composed of individual elementary objects which occurred through the combined use of Grammar and the corresponding rules. This methodology can be used to produce 3D models in various forms (e.g., CAD, BIM).

Another model-driven category is footprint-based methods. Simple buildings as the ones encountered in rural or suburban areas can be approximated by rectangular footprints and parametrized standard roof shapes. Several investigations try to group and categorize the different roof shapes. Milde & Brenner (2009) and Kada (2009) present a description of the most common roof shapes. Haala & Kada (2010) support that if roof details such as dormers and chimneys are not required, buildings may be automatically recognized and parametrized even from low density data.

In Taillandier (2005) a footprint-based approach is proposed. The reconstruction of buildings is achieved by extruding the given footprints to a uniform building eaves height. Then it is hypothesized that sloped roof faces pass through every extruded line segment, which an exhaustive search over all possible plane intersections verifies. From the DEM, the precise eaves height and all slopes are determined by a least squares' estimation and a polyhedral building model is constructed from the intersection of the verified planes. Such approaches perform well on symmetric roof shapes with global eaves height and central ridge, but fail in cases of complex shapes and height discontinuities. In order to overcome this throwback some approaches try to circumvent this problem by hypothesizing the height discontinuities from the footprint and decomposing it accordingly. Kada and McKinley (2009) and Kada (2009) exploit this idea and decomposes the given building footprints into wings and fits basic roof shapes into these. Due to the complexity of building footprints and the limited geometric accuracy of cadastral maps, exact decompositions that fit well with the roof shapes are very hard to generate. The spatial partition is therefore not generated by decomposing a footprint itself, but is rather recreated from scratch by decomposing an enlarged block along the approximated linear features of the building. The resulting 2D cells are then compared with the original footprint and the ones with a low overlap are discarded. The remaining cells form together a generalized shape of the building's footprint. Points that are inside a cell are compared to a library of template roof shapes. A cell is given the shape for which most points fit with regard to their normal direction. If the decomposition of the ground plan generates too many cells, then the roof parts are sometimes divided over two or more cells. This makes it difficult or even impossible to fit the parametric roof shapes. Vallet et al. (2009) therefore do not only split the footprints along their principal directions, but also merge them again if necessary.

3.2.3 Data-driven methods

Data-driven or bottom-up approaches are more flexible as they do not require any prior knowledge about a specific building structure. In recent literature, the majority of the proposed data-driven methods tend to extract points related to the building roof structure and classify them into different roof planes with 2D topology. The geometry of the roof can be described by a set of geometric primitives (planes, lines etc.) on which the 3D reconstruction procedure is based. Points can be clustered into planes based on similar attributes, such as: normal vectors, distance to a localized fitted plane or height similarities (Rottensteiner et al., 2014). Current data-driven methodologies and algorithms may be divided into four (4) general categories: (a) plane fitting based methods, (b) filtering and thresholding-based methods, (c) segmentation and growing based methods and (d) supervised classification methods (Makantasis et al., 2015; Alidoost & Arefi, 2016).

In the recent literature there are several approaches trying to apply *plane fitting-based* methods on 3D point clouds, derived either from active sensors (e.g., LiDAR) or produced through photogrammetric procedures. The most well-known examples of algorithms used in this category are Random Sample Consensus (RANSAC) algorithms (Fischler & Bolles, 1981), Least Squares planar fitting algorithms (Omidalizarandi & Saadatseresgt, 2013) and plane fitting based algorithms (McClune et al., 2016). Wang (2016), proposed a methodology for the detection and extraction of buildings roof outlines utilizing a dense point cloud derived from high-resolution aerial imagery. For the generation of the dense point cloud an automated Semi-Global Matching (SGM) method (Hirschmüller, 2008) is proposed. The proposed methodology tends to extract the ground surface using a polynomial surface adaptation method and then extract the buildings volumes by the production of nDSM (normalized DSM). Utilizing various radiometric and other criteria for the classification of all the elements located on building’s roof top, the outline of the roof is extracted through a split-and-merge method. It is noted that the proposed methodology can be applied in areas with complex types of buildings but not in densely urbanized areas.

In recent literature, *Filtering and Thresholding based methods*, especially in case of aerial images for extracting building outlines utilizing edge detectors, are widespread. Wang (2012) assumed that roof levels are composed by a set of points and lines. Through the use of the Movarec point detector and the Canny edge detector (Canny, 1986) the points and lines, respectively, describing the roof levels are extracted. Finally, these features are then matched and the desired 3D model is produced. Dal Poz et al. (2016) proposed a methodology for the extraction of buildings boundaries and roof ridgelines, with the combined use of high-resolution aerial images and ALS (Aerial Laser Scanner) data. ALS data are utilized to limit the amount of straight lines representing the roof boundaries and then, Steger line detector and Canny edge detector are applied to the images, to identify lines within the limited area of the interior of the polyhedrons. Awrangjeb et al. (2012), also used the Canny operator to extract lines from orthophotos while utilizing LIDAR data to categorize them. They also identified and removed vegetation from regeneration processes utilizing the Normalized Difference Vegetation Index (NDVI) and entropy images.

Köhn et al. (2016), proposed a different method for the detection and reconstruction of the building roof, using aerial images. A high resolution DSM was derived based on an SGM algorithm. The exterior and interior orientations of all images were estimated through bundle adjustment using the GNSS/IMU measurements. In the first step, the DSM was normalized based on morphological grayscale reconstruction. The derived nDSM includes the volumes above the ground, identifying the potential building positions. A line segment detector (LSD) is applied, in order to identify straight line segments through a region growing method among pixels with similar intensity and orientation. An assumption about the buildings shape rectangularity was made, in order to identify them. Then, a RANSAC-based plane fitting procedure is applied to the pixels in each segment by which the 3D building roofs are reconstructed. Apart from the above, Curve Propagation Techniques (snakes, geometrical snakes or active contours, deformable models) have shown encouraging results both to identify buildings and roads (Karantzalos & Argialas, 2009; Mayer, 1999; Mena, 2003; Kass et al., 1987; Cohen, 1991; Gruen & Li, 1997; Jeon et al., 2002; Kabolizade et al., 2010) and thus at the reconstruction procedures.

Another widely used reconstruction category deals with *Segmentation and growing based methods*. Rottensteiner et al. (2014), argue that area-based reconstruction tends to favor the use of lidar data in the form of point clouds or raster DSMs. Points can be clustered into planes based on similar attributes, such as: normal vectors, distance to a localized fitted plane or height similarity. This clustering is performed using methods such as: region growing based algorithms, 3D Hough-transform or the RANSAC algorithm. While many approaches have tried to fit planes to extract surfaces, an alternative and under-explored approach is the use of cross sections for segmenting planar features. This approach is called scan line segmentation. However, this approach tends to be more computationally expensive compared to the planar detection due to the number of points being tested for clustering. Planar segmentation results depend on the correct determination of threshold parameters, such as the neighborhood used to calculate the attribute, and incorrect results may arise in areas with low point density and complex structures (Rottensteiner et al., 2014). While surface extraction and planar fitting approaches may accurately detect planes and perform well in the presence of noise, they tend to lead to over and under segmentation. Research has shown that planes can be extracted by segmenting along cross sections of a surface and then performing region growing. McClune et al. (2014) proposed a methodology to derive the geometry of building boundaries using aerial images. At first the roof level is identified using the DSM. By means of along cross sections method, the 2D sections height differences are examined using the DSM. The parts with intense height differences are usually sections of roof boundaries. Canny edge detector used in order to find additional roof features. Omidalizarandi & Saadatseresgt (2013) performed region growing on image-based point clouds to form planar segments. However, it was found that errors from planar segmentation may arise at the location of the planar boundaries. These boundary errors can be overcome by combining feature-based and area-based methods, with the extraction of edges from imagery tending to form a post-processing step to refine the boundary of planes from lidar data. Besides aerial or LIDAR data, mobile-phone images are recently used for photogrammetric reconstruction.

Furthermore, McClune et al. (2016) proposed a methodology aiming to identify and reconstruct the roof tops of buildings, using aerial imagery with large overlap in both length and width. With proper image processing the corresponding DSM is produced. Next, the normalized DSM (nDSM) is generated, utilizing the elevation data provided by the available topographic diagram (DTM = DSM - nDSM). Buildings footprints depicted in the topographic diagram are used as guides in the identification process of the roof tops and their characteristics. Through the Canny operator the roof tops edges are detected, and then the altitudes from the nDSM are adjusted to them. Minimum Square Method (MST) is utilized for the determination of the optimal adjustable edges at the boundaries. Finally, the adjustment of the roof level is done through the region growing method with edges.

In Zhang et al. (2016), an alternative method of complete reconstruction of buildings utilizing region-growing methods, is proposed. As initial data LIDAR data in combination with images captured with smart phones, are selected. Through the combined use of LIDAR data and mobile images, the coverage of respectively the roofs and the facades of the buildings, is achieved. Mobile images are grouped using location information (GPS) stored in the metadata file that accompanies the images (Exchangeable Image File - Exif). For each of the image groups, a dense point cloud is generated using the SfM and PMVS algorithms. Then, the LIDAR cloud is segmented through the region growing algorithm in order to determine the possible locations (surfaces) of the buildings. For each of the point clouds, that represent a unit building, the roof boundary lines are extracted. with the help of the normal vectors. Due to the reduced accuracy offered by the GPS of the mobile device, the mapping between the clouds does not meet the requirements of the reconstruction procedures. In order to accurately combine the two data sets, the Coherent Drift Point (CPD) algorithm is used (Myronenko & Song, 2010), in order to achieve an exact match between the extracted boundaries of the studied building. In order to make an accurate mapping of the data in the 3D space, the middle altitude point of the studied building is calculated in each of the cloud points. Finally, the matching between the two data sets is achieved by merging the midpoints. The proposed methodology is applied to one building at a time. It is expected to be able to be implemented on a larger scale in the future. It produces satisfactory results for buildings with complex boundary geometry. However, it may not be effective in the case of box-shaped buildings due to the lack of a variety of features.

Supervised classification methods, such as Deep Learning methods (Makantasis et al., 2015) are a class of machines that can learn a hierarchy of features by building high-level features from low-level ones, thereby automating the process of feature construction for the problem at hand. As examples of Deep Learning models the Convolutional Neural Networks – CNN, the Stacked Auto-Encoders and the Deep Belief Networks may be mentioned. CNNs consist a type of deep models, which apply trainable filters and pooling operations on the raw input, resulting in a hierarchy of increasingly complex features. Generally, there are two common approaches for training a CNN model, such as training from scratch with random values of weights, as well as fine-tuning of a pre-trained model. CNN is a kind of feed-forward neural network with the multilayer perception concept which consists of a number of convolutional and subsampling layers in an adaptable structure and it is widely used in pattern recognition and object detection application. In literature, there is a limited number of studies on the detection and identification of 3D structures based on CNNs using remote sensing data. Alidoost & Arefi (2016) proposed a model-based approach for the automatic recognition of the building roof models (such as flat, gable, gabled, hipped, etc.) based on a supervised pre-trained Convolutional Neural Network (CNN) framework using LIDAR data and aerial orthophotos.

Unlike traditional classification-based techniques for building detection, CNNs can automatically extract features and proceed with classifications through sequential convolutional and connected layers, as a one-step method. While the feature extraction is learned from the data itself, better generalization is achieved, in contrast with traditional methods which require a large amount of manual intervention. However, in case of large-scale areas, the memory cost of CNNs is massive and the processing efficiency is reduced significantly. This problem is improved through fully convolutional networks (FCNs), by replacing the fully connected layer with upsampling operations, allowing the pixel-to-pixel classification of an image. However, FCNs and other similar convolutional encoder-decoder models, such as SegNet (Badrinarayanan et al., 2017) and DeconvNet (Noh et al., 2015), use only a part of layers in order to generate the final output, leading to poor results in terms of edge accuracy. To overcome this weakness, one of the state-of-the-art fully convolutional model, U-Net (Ronneberger et al., 2015), adopts a bottom-up/top-down approach with skip connections, in order to combine both lower and higher layers to generate the final output, achieving better performance. These skip connections used in U-Net, fast-forward high-resolution feature maps from the encoder to the decoder network, resulting in the fusion of semantically dissimilar feature maps. However, by dealing with semantically similar feature maps, the optimum learning task may become easier (Zhou et al., 2018).

During the past decades, building detection from remote sensing imagery using deep learning methods has drawn considerable attention. Chhor et al., (2017), developed a CNN based on U-Net architecture, for buildings detection on satellite images, using few data with relatively low resolution. Ground truth labels for training, are extracted from OpenStreetMaps (OSM, 2022). The proposed approach achieved satisfying accuracy, with room for improvements. Wu et al. (2018a), proposed a multi-constrained fully convolutional network (MC-FCN) to perform an end-to-end building segmentation, utilizing aerial imagery. The MC-FCN adopts U-Net as backend and introduce multi-constraints of corresponding outputs, enhancing the multi-scale feature representation. The proposed MC-FCN method outperforms the classic FCN and the adaptive boosting method using features extracted by the histogram of oriented gradients. Wu et al. (2018b), proposed a boundary regulated network (BR-Net), which utilizes both local and global information, to perform roof segmentation and outline extraction. BR-Net utilizes a modified U-Net model, replacing the traditional ReLU with LeakyReLU (with a=1) as shared backend. Also, extra boundary loss is proposed to regulate the model. Due to the restriction and regulation of additional boundary information, the proposed model can achieve superior performance compared to existing methods. Bokhovkin & Burnaev (2019), proposed a novel loss function, namely a differentiable surrogate of a metric accounting accuracy of boundary detection. The main objective of this research is to optimize the accuracy of buildings borders, by exploiting the capabilities of both IoU (Intersection of Union) and BF_1 loss through a weighted sum. The proposed loss function is validated with several modifications of U-Net on synthetic and real-world datasets. CNNs trained with the proposed loss function, outperform baseline methods in terms of IoU score. Sahu & Ohri (2019), proposed an interesting technique, aiming to extract buildings in densely urbanized areas using medium resolution satellite/UAV orthoimages. As CNN, a standard U-Net model is utilized, with the difference that after every convolution a batch normalization layer is added, in order to label every pixel in the image. A post-processing pipeline is proposed, for separating connected binary blobs of buildings and converting it into GIS layer for further analysis as well as for generating 3D buildings.

Furthermore, many researchers have used multi-class Support Vector Machine (SVM) classification for land use detection of urban areas from aerial or high-resolution satellite images. SVM is a supervised non-parametric statistical learning technique (Burges, 1998; Vapnik, 1999). SVM need training data that optimize the separation of the classes rather than describing the classes themselves. Training the SVM with a Gaussian Radial Basis Function (RBF) requires setting two parameters: regularization parameter that controls the trade-off between maximizing the margin and minimizing the training error, and kernel width. SVM classifier provides four types of kernels: linear, polynomial, RBF, and sigmoid (Sarp et al., 2014). The RBF kernel works well in most cases. Tuia et al. (2010) performed SVM classification using composite kernels for the classification of high-resolution urban images and concluded that a significant increase in the classification accuracy was achieved when the spatial information was used. Sarp et al. (2014) proposed a method for the automatic detection of buildings and changes in buildings after an earthquake, utilizing orthophoto images and point clouds from stereo matching data. In the first step the classification of the high-resolution pre- and post-event Red-Green-Blue (RGB) orthophoto images (ortho RGB) conducted, using SVM classification procedure to extract the building areas. In the second step, a normalized Digital Surface Model (nDSM) band derived from point clouds and Digital Terrain Model (DTM) is integrated with the SVM classification (nDSM + orthoRGB). Finally, a building damage assessment is performed through a comparison between two independent classification results from pre- and post-event data. The main conclusion was that using the spectral information as well as the elevation information from point cloud as additional bands, leads to a significant accuracy increment. Vakalopoulou et al. (2015) developed a method of locating buildings from high resolution satellite images. In this process vector features used to train a binary SVM classifier to separate building and non-building objects. Then, a MRF model was used to extract the best classification results. Zhang et al. (2015) proposed two search algorithms to localize objects with high accuracy based on Bayesian optimization and also a deep learning framework based on a structured SVM objective function and CNN classifier. The results on PASCAL VOC 2007 and 2012 benchmarks highlight the significant improvement on detection performance.

3.2.3.1 Surface Reconstruction

It is desirable for a reconstruction algorithm to produce a reliable and detailed representation of the studied object or scene. This objective is challenged by the significant imperfections that are contained in 3D point clouds, making this expectation to seem unrealistic. However, for certain methods it is still possible to obtain such valuable shape representation. Through numerous approaches, surface reconstruction methods can be divided into two (2) broad categories: (a) combinatorial methods and (b) implicit methods.

Combinatorial algorithms introduce relationships between the points of the input data. These algorithms tend to divide the 3D space utilizing a tetrahedralization or voxel grid, clustering data through a topological analysis using an analysis of cells (Amenta et al., 2001; Boissonnat & Oudot, 2005; Podolak & Rusinkiewicz, 2005), eigenvector computation (Kolluri et al., 2004), or graph cut (Labatut et al., 2009; Hornung & Kobbelt, 2006). The main disadvantage of these methods is that maintain the noise or corruption included in the initial data. An example of such an algorithm is the Ball pivoting algorithm (Bernardini et al., 1999). The basic idea of this algorithm is that a ball is moving around the 3D space trying to connect three points at a time. The ball is initially connected with two points of the input data and moving around until it intersects with a third point. Thus, triangles between the points of the input cloud are created. The majority of current combinatorial algorithms are engaged in forming schemes through triangulation utilizing Delaunay triangulation algorithm. Hence in recent literature these methods are also referred as Delaunay-based methods (Labatut et al., 2009).

On the other hand, implicit functions present a more robust approach. In cases of noisy data, a common approach is to fit points using the zero set of an implicit function. Implicit methods usually based on the interpolation of the data or on approximating a surface near the input data. The most commonly known implicit methods of the latter case, are marching cubes (Lorensen & Cline, 1987) and Poisson surface reconstruction (Kazhdan, 2006; Kazhdan & Hoppe, 2013). Poisson surface reconstruction (Kazhdan, 2006) is a well-known technique, able to produce watertight surfaces from oriented point samples. While the most implementations encountered in the current literature, use Poisson reconstruction in order to reconstruct surfaces from data derived by active sensors (e.g., terrestrial scanners) (Kazhdan, 2006; Kazhdan and Hoppe, 2013), this technique may provide very promising results utilizing other data sources (e.g., dense cloud from aerial images). Poisson surface reconstruction is resilient to noisy data and misregistration artifacts, and so it may be used for the reconstruction of complex urban scenes, following specific methodological steps. As it represents an implicit function, the produced result of this technique is a smooth approximate surface, positioned near the initial data. This encourages the usage of adaptive octree for the representation of the implicit function as well as for the solution of the Poisson system (Kazhdan, 2006). An important characteristic of Poisson surface reconstruction is the tendency to oversmooth the data. This may be undesirable in the most of the cases, but it can be adjusted to the current needs of each implementation, by defining the depth of the octree. The form of simple Poisson surface reconstruction is based on the normal field (inward pointing), which represents the boundary of a solid and may be interpreted as the gradient of the solid's indicator function. Thus, the main phases of Poisson surface reconstruction of a set of oriented points, may be defined as follows: (a) transformation of the oriented point cloud into a continuous vector field in 3D, (b) finding a scalar function whose gradients best match the vector field, and (c) extraction of the appropriate isosurface. In the proposed methodology screened Poisson reconstruction is utilized (Kazhdan & Hoppe, 2013). This approach is based on the traditional Poisson surface reconstruction (Kazhdan, 2006), incorporating positional constraints referred to the points data. By the term screening, a soft constraint that encourages the produced isosurface to pass through the input points, is implied. The main feature which differentiates the screened Poisson reconstruction over its traditional approach, is that the gradients are not constrained over the full 3D space, but the positional constraints are introduced only over the input points, which lie near a 2D manifold (Kazhdan and Hoppe, 2013).

3.2.4 Hybrid methods

In the last group of modelling approaches, the combination of model-driven and data-driven algorithms is used to have an optimal solution compensating the weakness of each method. Occasionally, multiple investigations about Hybrid methods are conducted, resulting in satisfactory results. Nguatem et. al. (2016), present a hybrid methodology for the automatic reconstruction of buildings at various levels of detail (Levels of Detail - LOD), following the definition for LODs as referred to in CityGML 2.0 (Groger et al., 2012). As input data, aerial images are utilized. Initially, the unsorted image sets are oriented (SIFT & VisualSFM) and depth maps are computed through SGM (Hirschmuller, 2008). By fusing these depth maps the reconstruction of the dense 3D point clouds is achieved (Kuhn et al., 2014). The point cloud is segmented into individual planes via the RANSAC algorithm. Adjacent regions with similar orientation are grouped forming candidate wall, ceiling and ground surfaces. This determines the volume of each candidate building. Eventually, an already known roof model (flat, dilapidated, etc.) is adapted to each of the buildings identified. The proposed methodology can work with the use of other data, such as LIDAR, while at the same time it can be developed using Deep Learning (Machine Learning) methods. However, despite the authors' pursuit for fully automation, the proposed methodology may be considered as semi-automatic whereas some of the intermediate steps, such as the scale rendering in the model, are performed manually.

3.3 Data extraction in support of 3D Cadastral mapping

3.3.1 Detection and reconstruction of noisy buildings' roof tops

The automatic detection and reconstruction of buildings outlines consist a difficult task which become even more challenging when dealing with buildings of complex geometry in densely populated areas, where the noise in the data is amplified by the existence of joined buildings with various non-structural man-mounted elements on their roof surface. However, the detection and removal of such noise may be achieved, based on some generic knowledge about buildings geometry and structure.

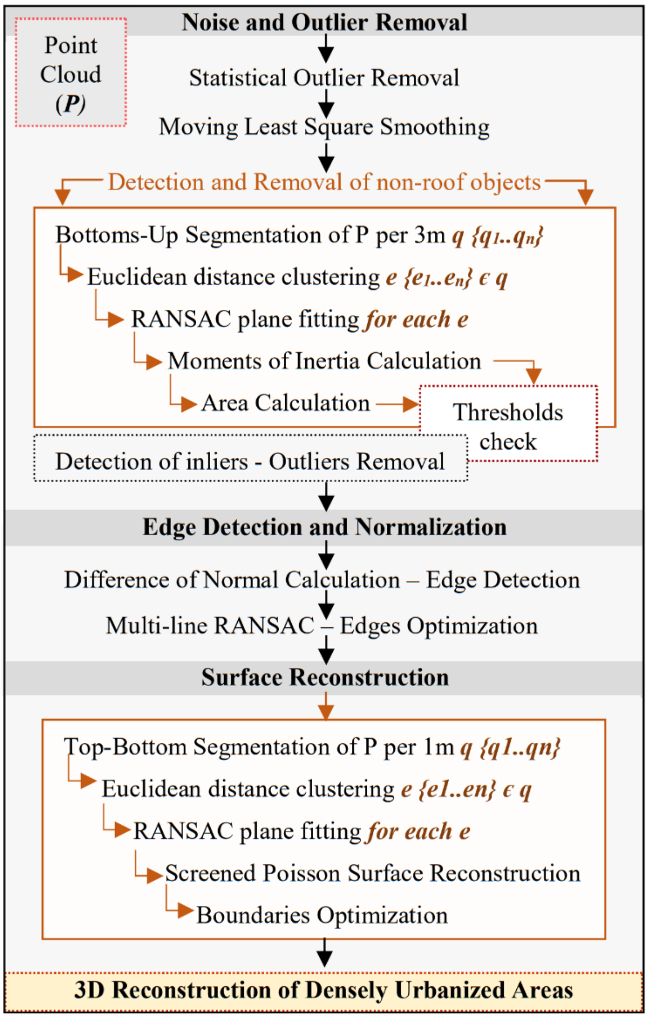


Figure 38. Workflow of the developed methodology.

3.3.1.1 *Proposed reconstruction methodology*

In this section, the methodology for the automatic 3D reconstruction of buildings roof tops, in densely urbanized areas, is presented. The proposed methodology is engaged in processing dense point cloud data, derived from (vertical) aerial images through dense mapping techniques. It consists of three (3) main stages (Figure 38): (i) Point Cloud Noise and Outlier Removal, (ii) Edge Detection and Normalization, and (iii) Partial Surface Reconstruction. Each stage includes a set of essential processing steps, aiming to improve the final outcome.

3.3.1.1.1 *Point Cloud Noise and Outlier Removal*

In the first stage of the developed methodology, the detection and removal of the noise included in the raw point cloud, is attempted. Besides the removal of the outliers, the point cloud is particularly examined aiming the identification and abstraction of any points set that does not belong to the roof surface or it is located on the surface without constituting its structural element. Through this step, the point cloud is simplified while the points representing adequately the underlying surface are distinguished and retained.

First, the outliers are filtered out through a statistical mathematical analysis, and then the remaining point cloud is optimized and smoothed, by a Moving Least Square (MLS) algorithm. Following, the detection and removal of non-roof objects is conducted, through a developed algorithm that utilizes a series of segmentation, plane fitting, mathematical models and calculations. These steps are described in detail below.

▪ *Statistical Outlier Removal (SOR)*

Outliers' removal is conducted through the analysis of the surrounding neighbors of a point, utilizing a mathematical analysis of their measured positions (Rusu, 2009). A point p_q may belong to the surface of an object if there are enough neighbors ($k \geq k_{min}$) in the vicinity of the query point. Certainly, point clouds densities vary accordingly to the current generation method and the particularities of the object's surface, such as shiny surfaces, depth discontinuities, or occlusions, creating false outliers and ghost structures. However, removing outliers is an essential step, leading to more reliable results and reduces the processing time.

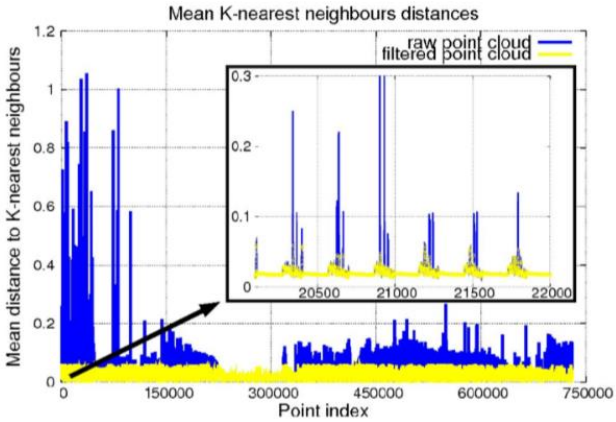


Figure 39. The mean distances to k = 30 neighbors before and after removal using α = 1 (Source: Rusu, 2009).

The developed methodology is based on a statistical analysis proposed by Rusu (2009). The algorithm examines each point of the point cloud ($p_q \in P$), calculating the mean distance *d* of its *k* neighbors. Then, a distribution over the mean distance space for the entire point cloud *P* is assembled and its mean μ_k and standard deviation σ_k are estimated. The main purpose is the production of a homogeneous point cloud, by excluding the points whose mean distance *d* differs greatest from the rest of the point of *P* (Figure 39). Thus, the remaining point cloud P^* derived according to Equation 1. In the proposed methodology the selected *k* value is equal to 50 and α is equal to 1.0.

$$P^* = \{p^*_q \in P | (\mu_k - \alpha \cdot \sigma_k) \leq \bar{d}^* \leq (\mu_k + \alpha \cdot \sigma_k) \} \qquad (1)$$

where P = initial point cloud

P^* = filtered point cloud

μ_k = mean deviation

σ_k = standard deviation

α = desired density restrictiveness factor

$\bar{d}$ = mean distance

▪ *Moving Least Square (MLS) smoothing*

In this section, another optimization step able to filter out the noise and produce a smoothed surface, is described. Moving least square algorithm (MLS) (Rusu et al., 2008; Alexa et al., 2003) tend to suppress outliers of a point cloud *P* by resampling (either upsampling or downsampling) and discarding unwanted data. Given a set of points *P*, MLS algorithm reproduce the complete smooth surface by fitting higher order bivariate polynomials to point in the vicinity of each query point p_q. In contrast to other interpolation or resampling techniques, MLS algorithm produce more robust results as the fitted surface passes through the original data. In the first step, the coordinates of each point p_q are normalized, utilizing the diagonal bounding box of the point cloud, ensuring a uniform distance between the points. The weight factor is estimated through Equation:

$$h = \mu_d + k * \sigma_d \qquad (2)$$

where h = weight factor

μ_d = mean deviation of the distribution of mean distances between points

σ_d = standard deviation of the distribution of mean distances between points

k = nearest neighbours of the query point p_q

Next, the initial point cloud is resampled by estimating an approximate set of points *Q*, which is presented as a set of equidistant grid points, located in vicinity of the initial point cloud *P*. These points will be projected onto a local reference plane fitted through their *k* nearest neighbors P^k. The points in the local neighbourhood of each query point p_q may be identified, either by the number *k* of their nearest neighbors or by using a fixed radius *r*, including a sub-set of *P*. Then, each point of *Q* is fitted to a surface which approximates the original data using a bivariate polynomial height function in a local Darboux frame. In most cases, 2nd order polynomials produce good results as the most areas are either planar or curved in only one direction. In the developed methodology where the buildings' roof tops may be estimated approximately through planar surfaces, the utilization of such a MLS algorithm with 2nd order polynomial function is preferred. In this approach a MLS algorithm proposed by Rusu (2009) is selected. This algorithm is utilized in order to simply resample data without upsampling or downsampling the initial point cloud. Thus, the MLS algorithm optimize data position with respect to the approximate underlying smooth surface. The produced smoothed point cloud contains the same number of points with the initial cloud, possibly moved to a better approximate position if is needed.

- *Detection and Removal of non-roof objects*

Another category of points that must be detected and excluded from the point cloud, are points that do not belong to buildings roof tops but to other structures that exist on the roof (e.g., chimneys) or at lower height levels (e.g., balconies). All these points are noise and strongly affect the overall reconstruction pipeline, resulting to inconsistent representations of the roofs structure. The detection and removal of such elements is essential. For the automatic extraction and reconstruction of buildings, some generic knowledge on buildings should be considered and utilized as geometric constraints. Building or floor height, size, shape regularity, roof surface smoothness, homogeneity and occlusions by trees or shadows, are some of the geometric and radiometric contextual properties about buildings structure and errors sources (Wang, 2016). In cases of densely urbanized areas, where buildings are partially-attached to neighboring buildings with varying heights, the detection and removal of non-roof objects requires a bottom-up analysis of the building structure with respect to adequate geometric constraints.

The developed algorithm follows a sequence of five (5) discrete steps, trying to remove non-roof elements. The first step includes a bottoms-up segmentation of the point cloud. The algorithm searches the point cloud in order to find the point with the lower height and continues the segmentation by grouping points whose height difference is less than 3m. As the initial point cloud may include points representing building's parts of a lower level, the 3m threshold is chosen as it corresponds to a typical floor height. This assumption divides the search space into smaller parts, facilitating the imposition of geometric constraints. Then, each of the height clusters derived from the first step, is processed separately. Each one of the height clusters include points with height difference less than 3 m. However, their distribution through the horizontal plane defined by X and Y axis, varies. Thus, for each height cluster a simple Euclidean distance thresholdbased clustering algorithm (Rusu, 2009) is applied with a distance tolerance of 1m, in order to identify the individual points groups. At this phase, the point cloud is segmented in individual parts, each of which represents an element or object of buildings surfaces. Then, the process continues on the basis of certain assumptions. As the surface of each building consists of several planar segments, a RANSAC based plane fitting algorithm (Fischler & Bolles, 1981) with a threshold of 0.5 m is applied to each one of the grouped points of the produced height clusters. The threshold of 0.5 m is selected, in order to optimize the plane detection procedure, removing non-roof objects (noise) with height less than 0.5 m. Subsequently, an initial normalization of the points position according to the detected planar segments is conducted, through the projection of the inliers on the detected plane and the removal of the outliers from the point cloud.

In the next step, each one of the detected groups, which include the remaining points after the normalization of the point cloud, is checked against two certain criteria. The first criterion refers to a shape constrain. A group of points belonging to an elevation level lower than the roof, in most cases, represents a balcony. This building element consist a non-roof structure, causing errors to the reconstruction procedure. However, it has some structural and geometric characteristics able to differentiate it from the rest building's elements. The basic dimensions of a balcony, length and width, are disproportionate resulting to a high valued ratio. This finding is used as a criterion for the detection of such elongated features in the point cloud and remove them. Subsequently, for each one of the groups of points, we calculate and construct the respective oriented bounding box (OBB), based on eccentricity and moment of inertia (Pratt, 2001; MOI, 2018). First of all, the covariance matrix is calculated and its eigen values and vectors are extracted. An iteration process begins where the major eigen vector is rotated continuously, around the other eigen vectors. For every current axis moment of inertia and eccentricity is calculated. Then, eccentricity is calculated for the obtained projection. In order to find the dimensions of the OBB, a transformation into the local frame of the box is calculated, keeping track of the minimum and maximum coordinates in each direction. Thus, utilizing the coordinates of OBBs corners, the calculation of its minimum and maximum sides is conducted. As threshold for the acceptance of a group of points as roof part, the ratio of 4 is selected, as it provides the best detection performance. The definition of the ratio is calculated through the Equation 3.

$$ratio_{OBB} = \frac{Dmax_{OBB}}{Dmin_{OBB}} \leq 4 \qquad (3)$$

where $ratio_{OBB}$ = ratio between the max and min OBB distances

$Dmax_{OBB}$ = maximum length of OBB

$Dmin_{OBB}$ = minimum length of OBB

The second criterion refers to an area constrain. An object may be included in the main structure of a building only if its area exceeds a certain threshold. Otherwise, this object consists a non-structural object (e.g., chimneys) causing noise, and thus need to be excluded from the point cloud. As minimum accepted area of a group of point, $10m^2$ is selected. This size refers to small objects which may be included in the main structure of the building. However, the calculated area concerns a surface with multiple anomalies, and thus the minimum area assumption consists a satisfactory threshold for the developed methodology.

3.3.1.1.2 Edge Detection and Normalization

One of the main structural features of buildings' roof tops is the regularity of their shapes. The roof tops edges are smooth and in the majority of cases their intersections are orthogonal. The normalization of edge points is of great importance, as the edges in the point cloud presented as "trembling lines" due to the non-uniform distribution of points, along with the remaining noise in the data (e.g., due to occlusions). In the developed methodology, edge detection is conducted with the multi-scale difference of normals (DoN) operator (Ioannou et al., 2012). DoN operator, is similar to the Difference of Gaussians (DoG) operator, providing very good results in identifying points saliency according to scale. To identify edges points, DoN operator utilize the estimated surface normal map of the point cloud. As the surface normals estimated at any radius r, reflect the underlying geometry of the surface at the scale of each support radius, this method is appropriate to identify areas with high differences which present the edges areas. In the literature there are several approaches arguing that edge detection may be conducted based on the surface curvature changes, but this is not the only solution. While DoN seems to be simple enough, is shown to be surprisingly powerful as normals are less effected by noise compared to higher order derivative quantities such as curvature (Ioannou et al., 2012). In the proposed methodology normals estimation is conducted utilizing the approach proposed by Alexa et al. (2003) and extended by Rusu et al. (2008). According to this approach, normals estimation is conducted according to the characteristics of the points which are included in a support radius r around the query point p. This radius determines the scale in the surface structure which the normal represents. The basic idea of the DoN operator, is to compare the responses of the surface normals between two different radius r1 < r2. DoN operator Δn is calculated for each point p of the point cloud P. The utilization of the surface normals for a small and a large radius is selected in order to examine the upmost of the surface features. A small support radius is affected by small-scale surface structures. In contrast a large support radius is more robust in small-scale effects and represent the geometry of larger scale surface structures (Figure 40).

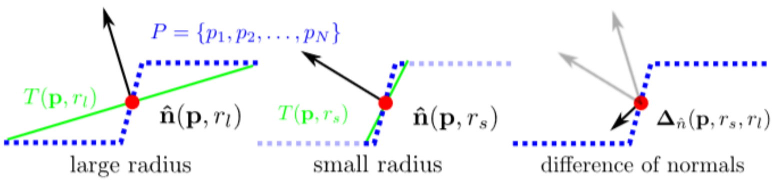


Figure 40. The meaning of large (left), small support radius (middle) and the calculated DoN operator (right) (Source: Ioannou et al., 2012).

DoN is calculated for each point *p* in the point cloud *P*, and then a vector map is created. As each DoN presents the normalized sum of two normal vectors, its magnitude is varying through the values [0,1]. Setting a certain threshold on this magnitude, the extraction of the points related to the edges are extracted. In the proposed methodology a small support radius of 1m and a large support radius of 10m are used. As DoN threshold a value of 0.80 is selected, as presented the best performance. After extracting the detected edges points, a RANSAC based line fitting algorithm (Fischler & Bolles, 1981; Rusu, 2009) with a threshold of 0.5m, is imposed upon them. Thus, edges points are normalized, by projecting them onto the estimated line, in order to satisfy as much as possible the regularity criterion of roofs structure.

3.3.1.1.3 Partial Surface Reconstruction

In this phase the 3D reconstruction based on the refined point cloud derived from the previous steps, is attempted, following several processing steps. For the reconstruction process, the screened Poisson surface reconstruction technique (Kazhdan & Hoppe, 2013) is selected, as its resilient to noisy data, similar to those dealt by the developed approach.

The main idea of the developed algorithm is to provide a top-down approach, reconstructing partially the detected planar surfaces, constructing the buildings' roof tops. Because of the high level noise present in the data of an urban scene, the reconstruction of the planar roof tops surfaces is not a trivial neither an easy target. The algorithmic procedure followed in this phase, consist of five (5) steps. In the first step, a top-down segmentation per 1m, of the refined points, is conducted. The algorithm searches the point cloud in order to find the highest point and continues the segmentation by grouping points whose height difference is less than 1m. The selection of this threshold for the segmentation process, is based on the assumption that in each section of 1m of the vertical dimension of a building it is possible to exist either a planar surface or a vertical surface. As the proposed procedure refers to point clouds produced using vertical aerial images, points presenting the vertical elements of a building may be very few and rarely present in the point cloud. Thus, at each section of 1m the existence of a planar surface, is very likely. However, in contrast with the possible distribution of planar surfaces along the vertical direction, their horizontal distribution is not obeying the same premise. In the horizontal direction, building's roof tops may be connected semi-detached or detached with the neighboring buildings. Thus, in the next step, a simple Euclidean distance threshold-based clustering algorithm is applied to each one of the height clusters, with a distance tolerance of 3 m in order to identify the individual points groups, which represent neighboring planar surfaces. Subsequently, a RANSAC based plane fitting algorithm with a threshold of 0.5 m is applied to each one of the grouped points of the produced height clusters. Subsequently, the detected inliers are projected on the estimated plane and the outliers are removed from the point cloud. This step is important for optimizing each one of the grouped points, reducing the remaining noise from the previous stages. The final acceptance of each point group as possible representation of a building's planar element, is done if the corresponding area exceeds 5 m^2.

Once a group of points is optimized and checked against the threshold of 5 m^2, the surface reconstruction of the corresponding planar surface is conducted, through utilizing screened Poisson surface reconstruction (Kazhdan & Hoppe, 2013), with octree depth equal to 8. Each point group was reconstructed separately to produce surfaces best fitted to these certain points and avoiding to change the final shape of the surface, in order to fit to the whole point cloud. The next step, concerns a particularity that presented from screened Poisson surface reconstruction algorithm. Poisson surface reconstruction algorithm tends to surround the data, in order to achieve the best possible fitting of the calculated surface. Thus, unnecessary surface extensions are created at the boundaries of the studied object. These extensions need to be removed, in order to produce a reliable reconstruction. For this reason, the concave's hull polygon (Rusu, 2009) referred to each one of the point groups, is calculated. Subsequently, the final reconstruction presenting the roof tops of the buildings in densely urban areas, is produced cropping Poisson Surface along the boundaries of Concave's Hull polygon with alpha parameter equal to 5.

3.3.1.2 Experimental Results

In this section, the reconstruction software that has been developed for the implementation of the methodology outlined in section 3.2 is presented, along with the test dataset and the achieved results.

3.3.1.2.1 Developed software

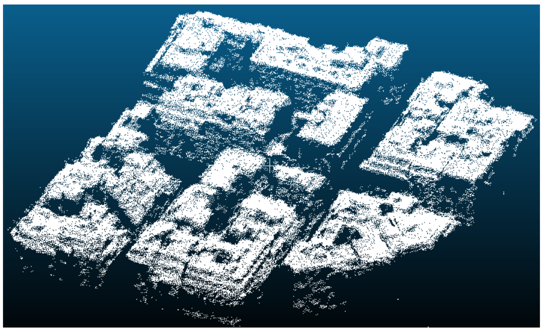
The developed software implemented in the programming language C++, utilizing the libraries of PCL - Point Cloud Library 1.8.0 (PCL, 2018), VTK - Visualization Toolkit (VTK, 2018) and Eigen (Eigen, 2018). As input, an ASCII or Binary PCD (Point Cloud Data) file is required, including the coordinates X, Y, Z of the dense point cloud representing the urban scene, while a VTK file is produced as output, containing the reconstructed surface of the buildings' roof tops (Figure 41).

Figure 41. Workflow of the developed software.

3.3.1.2.2 Study Area and results

The test area is located in the center of Athens, Greece and is characterized by densely constructed semi-detached buildings with varying heights. As it is illustrated in the Figure 42 the separation between the individual roof tops is quite difficult. Subsequently, the roof tops of the buildings are not represented by smooth surfaces, but, on the contrary, they have complex geometry due to the existence of several non-structural objects positioned on their surfaces. As test data for the implementation of the developed methodology, a dense point cloud derived by a set of aerial images has been utilized (Figure 43 left). The point cloud was inserted in the developed software, so as the 3D reconstruction of buildings roof tops to be produced.

Figure 42. An orthophoto depicting the tested area of densely urbanized area in the center of Athens, Greece.



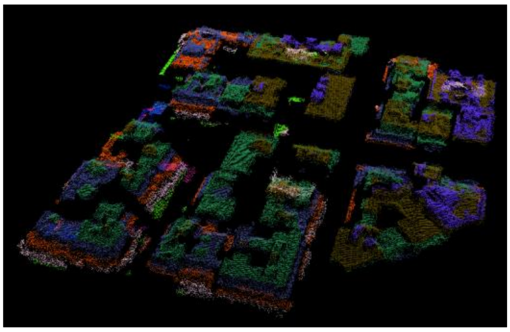


Figure 43.The input point cloud (left) and the segmented per 3m cleaned point cloud of the urban area (right).

At the first step of the developed methodology, outliers were removed from the initial point cloud and then a MLS smoothing with radius of 1m, is applied. A bottom to top segmentation of the point cloud was conducted, clustering the cloud into several height levels. As depicted in Figure 43 (right), the greater amount of noise has been removed. Each of the levels presented with a random selected color. In the next step, a Euclidean distance-based clustering was conducted to divide the point cloud into several groups of point, each one of them consist a candidate element of the building's structure. Each group was assessed against the shape and area criterions, as specified by the developed methodology (Section 3.2.1.3). In Figure 44, the results are presented. Each one of the detected group of points is presented with different random color, while the calculated oriented bounding boxes (OBB) on which the shape criterion is applied, are depicted with white color. The results of the first step were satisfactory, as the majority of noise and non-roof objects were detected and removed from the point cloud. However, in some cases non-roof structures, such as balconies, with area size more than 10 m^2 located in a lower level from the roof tops, remain in the cloud and presented as isolated segments. An example of such false-detected roof element, is depicted in a red circle in Figure 45 left. Also, the existence of repetitive elongated structures on the surface of the roof top, may be confused and be considered as noise, so these types of structures were also removed from the point cloud (Figure 45). Thus, the detection and optimization of the point cloud, removing outliers and non-roof elements, led to satisfactory results.

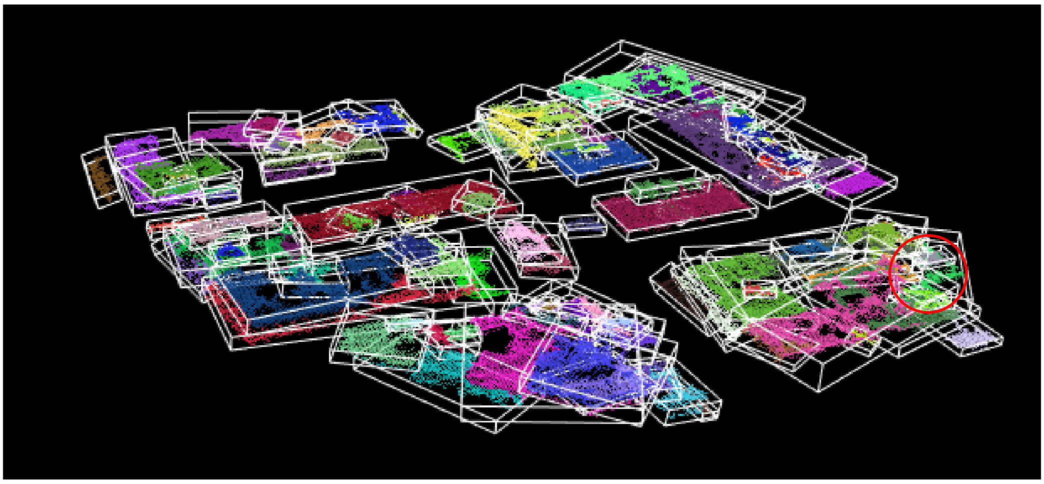


Figure 44. The detected roof elements presented in random color, surrounded by the OBB and a false-detection presented in the red circle.

Figure 45. An example of false-detection of noise. In the red circles, the removed roof top elements are presented in the orthophoto (left) and in the result of the first step of the developed methodology (right).

In the next step DoN operator was calculated, and the detected edges of the point cloud were refined. In Figure 46, the detected edges (left) and the refined point cloud (right) are presented. The refined boundaries were normalized to satisfy the shape regularity constrain. Finally, in the last step, the automatic surface reconstruction of the buildings' roof tops is conducted. The results are presented in Figure 47. Although there were some false-detections referring to roof and non-roof elements, the results are satisfactory as the final model represents reliably the buildings' roof tops, as smooth surfaces (Figure 47). The remaining noise is rarely presented as isolated surface segments far away from the buildings.

Figure 46. The detected edges (left) by DoN operator and the refined point cloud with normalized edges (right).

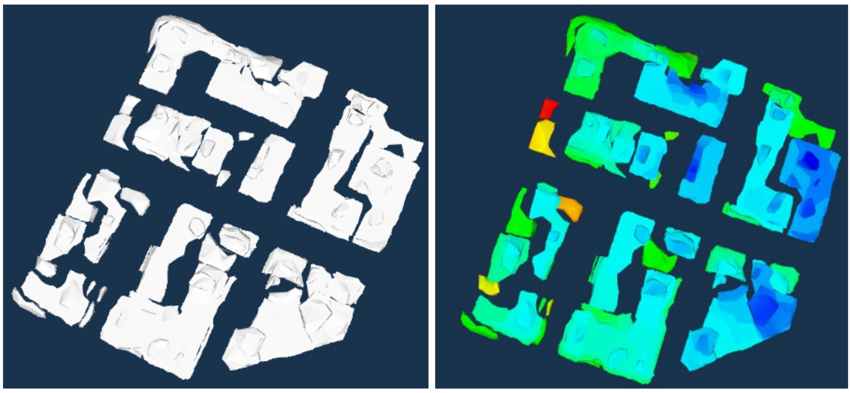


Figure 47. The result of the developed 3D reconstruction methodology (left) and the height colorized representation (right).

3.3.1.3 *Evaluation of results*

A comparison of the produced data with the corresponding reconstruction results derived from open-source software, is conducted. MeshLab and CloudCompare software were utilized for this comparison.

After inserting the test point cloud in each software, the noise was removed from the data, and the point normals were calculated based on a neighbourhood of k = 30 neighboring points. Then, the Screened Poisson Surface reconstruction algorithm with a depth of 8, was performed. In Figure 48, the results derived from MeshLab are illustrated. The building roof tops are presented as noisy rough surfaces, while the roof tops boundaries are depicted as wavy segments. At sparse positions on the roof tops surfaces, holes are appeared, changing the geometry of the roof tops. Furthermore, non-roof elements remain in the scene, complicated the processing procedures.

In Figure 49 the results derived from CloudCompare software are illustrated. The produced results are smoother than the previously achieved using the MeshLab software. However, the roof tops surfaces include multiple anomalies while their boundaries are difficult to be identified accurately. Furthermore, the noise referring to non-roof elements, as balconies and vertical walls, remains in the data while holes on roof tops surfaces are also encountered.

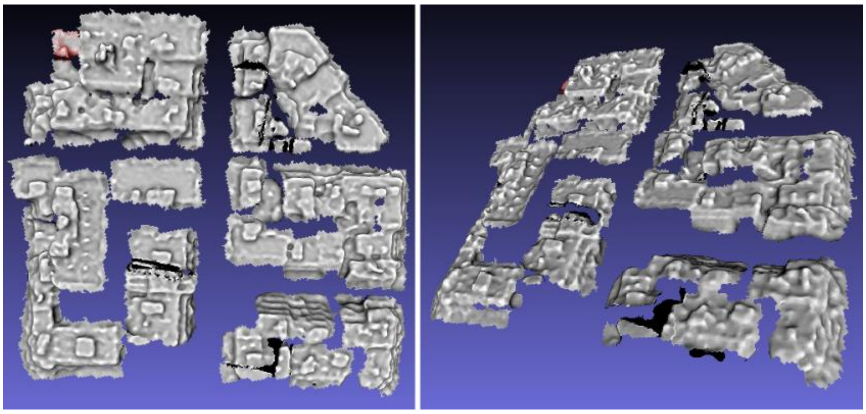


Figure 48. Screened Poisson Reconstruction of the tested area in MeshLab.

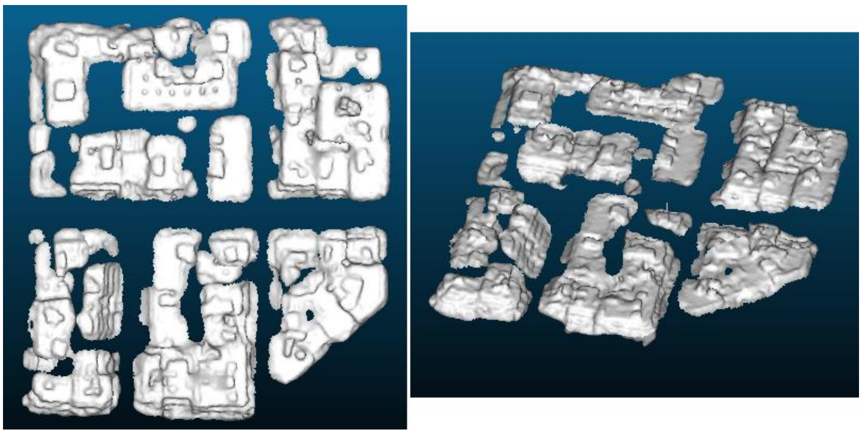


Figure 49. Screened Poisson Reconstruction of the tested area in CloudCompare.

3.3.1.4 Concluding remarks

Section 3.3. presents an alternative methodology, developed for the automated reconstruction of 3D point clouds of complex and densely urbanized areas. The developed methodology exploits state-of-the-art algorithms and techniques and combines them into a prototype sequence, introducing new algorithms whose operation is based on the geometry of the structural elements of the buildings and on simple logical claims.

The developed methodology consists of three (3) main phases, each of which comprises a set of processing steps. In the first phase, the point cloud is simplified and smoothed. Outliers and non-roof elements are detected and removed utilizing shape, position and area criteria. In the second phase, the geometry of the buildings' roof tops is optimized, by detecting and normalizing the edges. In the last phase, the partial reconstruction of the buildings' roof tops is conducted. A progressive process, utilizing a plane fitting algorithm in combination with Screened Poisson Surface Reconstruction is performed, while then the produced surfaces are further optimized.

A software tool is developed aiming to implement the 3D reconstruction methodology. The achieved results demonstrate that the developed methodology is able to detect non-roof top building's elements and exclude them from the dataset. By imposing several constrains referring to floor height, size, shape regularity, surface smoothness and homogeneity succeeds to produce a reliable and qualitative result, by presenting each building's roof top as a smooth and enough regular surface. Based to the abovementioned findings and assessments, appears that the developed software has been produced remarkable results, which outperforms over the compared open-sourced software. Although there were some false-detections concerning the roof and non-roof elements, this does not characterize and burden the whole reconstruction process. Taking into account the difficulties that the automated reconstruction processes face while using only dense point clouds from aerial imagery, the produced results are satisfactory as the final model represents reliably the buildings' roof tops as smooth surfaces, in most of the cases.

3.3.2 Detection and extraction of buildings outlines using deep learning

Unlike traditional classification-based techniques for building detection, convolutional neural networks (CNNs) can automatically extract features and proceed with classifications through sequential convolutional and connected layers, as a one-step method. While the feature extraction is learned from the data itself, better generalization is achieved, in contrast with traditional methods which require a large amount of manual intervention. However, in case of large-scale areas, the memory cost of CNNs is massive and the processing efficiency is reduced significantly. This problem is improved through fully convolutional networks (FCNs), by replacing the fully connected layer with upsampling operations, allowing the pixel-to-pixel classification of an image. However, FCNs and other similar convolutional encoder-decoder models, such as SegNet and DeconvNet, use only a part of layers in order to generate the final output, leading to poor results in terms of edge accuracy.

To overcome this weakness, one of the state-of-the-art fully convolutional model, U-Net (Ronneberger et al., 2015), adopts a bottom-up/top-down approach with skip connections, in order to combine both lower and higher layers to generate the final output, achieving better performance. These skip connections used in U-Net, fast-forward high-resolution feature maps from the encoder to the decoder network, resulting in the fusion of semantically dissimilar feature maps. However, by dealing with semantically similar feature maps, the optimum learning task may become easier (Zhou et al., 2018). U-Net++ model, present a slightly different segmentation architecture based on nested and dense skip connections. The underlying hypothesis is that the model can more effectively capture fine-grained details of the foreground objects when high-resolution feature maps from the encoder network are gradually enriched prior to fusion with the corresponding semantically rich feature maps from the decoder network. U-Net++ model has been extensively used for medical image segmentation, while lately it has been investigated for aerial image segmentation, becoming an interesting subject for further research in this field (Wang et al., 2022; Zhao et al., 2022; Peng et al., 2019).

For most of the tasks, it is important to distinguish buildings from each other, especially in densely populated urban areas where several complex infrastructures exist. Even with high-resolution imagery, the extraction of accurate information regarding buildings boundaries is narrowed. A thoughtful solution for this drawback is to increase the attention of the neural network towards the boundaries of adjacent buildings. Widely used loss functions, such as dice score, cross-entropy and direct IoU, do not provide enough sensitivity in cases of misaligned boundaries. To improve this matter BF_1 metric (Csurka et al., 2004) and its variants (Fernandez-Moral et al., 2018; Bokhovkin & Burnaev, 2019) may be utilized, in order to account better, the boundary pixels.

Moreover, buildings detection and extraction, is never the end product of a study. It consists an intermediate stage from which the analysis is done, in order to provide data useful in several applications based at industrial standard formats. Geospatial data such as buildings outlines, may be utilized in several GIS applications, providing a helpful basemap with multiple parameters to process and analyze. However, a raster output is not as utilitarian as a vector output, which can be processed, stored and maintained in an SQL (Structured Query Language) database (Sahu & Ohri, 2019).

3.3.2.1 Proposed Methodology

In this section, the proposed methodology is presented. The main objective of the developed methodology is to resolve a binary classification problem, providing a binary boundary-aware prediction about buildings and non-buildings instances. It consists of three (3) main stages, as illustrated in Figure 50.

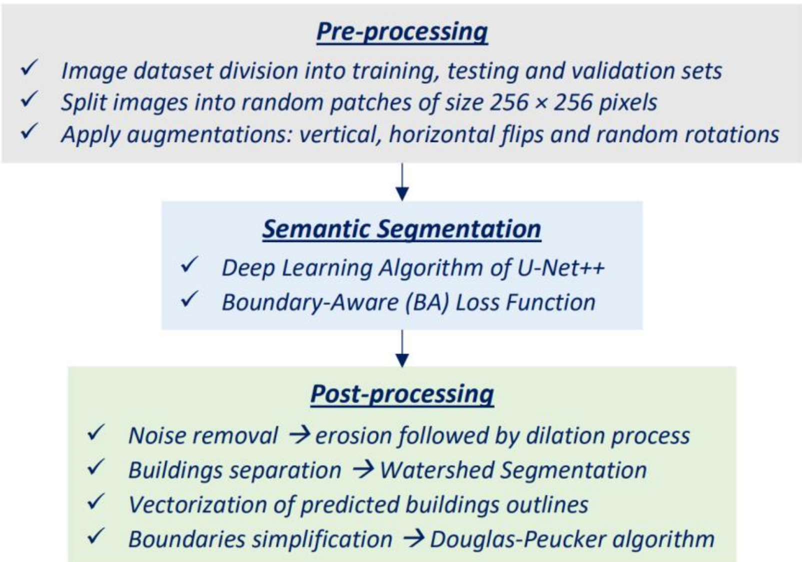


Figure 50. Workflow of the proposed methodology.

3.3.2.1.1 Pre-processing

The aerial imagery of the study area is pre-processed aiming to extract the proper input for training and testing the deep neural network. Initially, the data are divided into training and testing sets. Then, the training data are further divided into two parts: ideally, 70% of the data should be utilized for direct model training while the remaining 30% should be utilized for validation.

As higher resolution images require much more processing and memory to train deep CNNs, every orthophoto is split into random patches of size 256 × 256 aiming to make the classification binary problem computationally more feasible (Shorten & Khoshgoftaar, 2019). For both the images and the ground truth maps, strong augmentations should be applied including vertical, horizontal flips, normalization and shape manipulation, in order to increase the effectiveness of the CNNs operation, providing multiple potential representations of the studied scene.

3.3.2.1.2 Semantic Segmentation

For semantic binary segmentation of buildings outlines from aerial RGB imagery, the architecture of U-Net++ with the ResNet-50 (He et al., 2016) as backbone, is selected. Whilst in U-Net, the feature maps of the encoder and decoder are directly combined, in U-Net++, they undergo a dense convolution block where the number of the convolution layers depend on the pyramid level (Figure 51). Thus, the semantic level of the encoder feature maps gets closer to the corresponding feature maps in the decoder, simplifying the optimization problem. For this study the deep supervision in U-Net++ is preferred (Figure 51, shown red), in order to provide a more accurate outcome by averaging the outputs from all the segmentation branches.

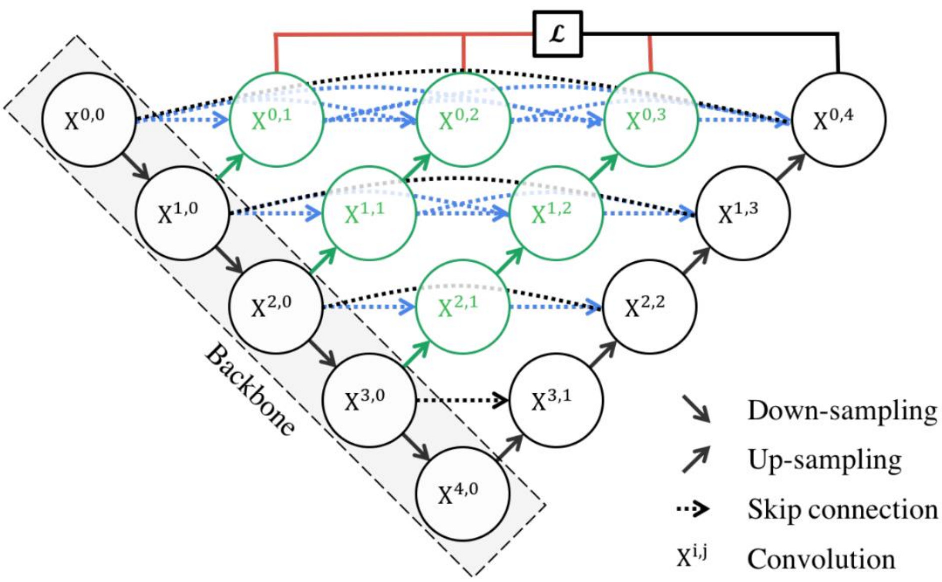


Figure 51. U-Net++ deep neural network architecture (Source: Zhou et al., 2018).

However, the performance of the model depends heavily on all the parameters that work in synergy. The segmentation and separation of different objects, especially in highly urbanized areas, is very challenging even with high-resolution imagery where more accurate information regarding buildings boundaries is presented. Therefore, it is important to utilize methods that draws the attention of CNNs, to the borders of the closely located objects.

The majority of CNNs for semantic segmentation, utilize the cross-entropy, dice score and direct IoU optimization as loss functions while training the network. However, these functions are not sensitive enough leading often to boundaries misalignments. To overcome this drawback Bokhovkin & Burnaev (2019), proposed a differentiated Boundary Loss (BL) function aiming to better account the pixels located towards the boundaries of the buildings.

Through combining the advantages of regular loss functions with BL, a more boundary-aware loss function may be generated utilizing the advantages of both methods. Bokhovkin & Burnaev (2019) stated that combining BL with IoU leads to better results as for boundaries identification, compared with other loss functions. However, in experiments it turned out that through combining BL with BCE (Binary Cross Entropy) metric, proportionally by 10% and 90% respectively, leads to better performances and more accurate boundaries identification, in cases of small datasets (Equation 4). This combination is obtained after testing different percentages, as described in the experiment section.

$$BA = 0.9*BCE + O.10*BL \qquad (4)$$

3.3.2.1.3 Post-Processing

Once the semantic segmentation with U-Net++ is completed, a set of raster predictions in binary format is generated, where each pixel is categorized as building or non-building. These raster data may consist a good representation of the built environment, however some remaining blobs make the output noisy. In addition, the raster format of the data makes difficult their exploitation for any further geospatial analysis, that needs the delineation of buildings as separate features. Furthermore, the extraction of buildings outlines in vector format may enhance more their potentials providing useful and reliable data for several GIS applications. Thus, a post-processing is necessary in order to appropriately configure the output of the neural network. Following, the three (3) main steps forming the post-processing procedure of the developed methodology, are presented and described. These steps concern: (i) the noise removal, (ii) the buildings separation, and (iii) the buildings outlines vectorization.

- *Noise removal*

In order to enhance the detection rate of the buildings and remove as much as possible noise, the basic morphological operation of erosion followed by dilation process, was applied on the binary output of U-Net++. These procedures tend to compress the foreground of the raster image while they expand the frontal area. Thus, the foreground regions are increased in size and the holes into the regions are decreased. With erosion the objects either shrink or become thinner (Equation 5) (Xu et al., 2020). Then, with dilation and filling, any holes in the interior of the object shrink, reducing object fragmentation (Equation 6). By connecting the output of these two processes the boundaries of the objects become more coherent providing a better output.

By denoting X as the input image coordinates and Y as the set of structuring element coordinates whose origin is f. Thus, the erosion and dilation of X by Y is calculated as follows:

$$X \oplus Y = \{f | (\widehat{Y})_f \cap X \neq \varphi\} \quad (5)$$

$$X \ominus Y = \{f | (Y)_f \cap X^c \neq \varphi\} \quad (6)$$

- *Buildings separation*

To separate the connections between buildings, we proceed with Watershed segmentation (Vincent & Soille, 1991). In this process the image is considered as a topographic landscape with ridges and valleys (Figure 52). The elevation values are defined by the grey values or gradient of the respective pixels. Having in mind a 3D representation of the landscape, the watershed segmentation decomposes an image into drainage basins. For each local minimum, a drainage basin includes all points whose path of steepest descent terminates at this minimum. Thus, the basins are separated from each other through the watersheds, as each pixel of the image is assigned either to a region or to a watershed.

However, in order to separate buildings a different perspective should be followed. Buildings have larger size that the blobs connections, meaning that the majority of their neighboring pixels belong to them and thus they are located in high grey values area. By finding the local maxima of the binary image, we ensure that the detected points lie inside the buildings' area and not along the connectivity blobs. Through utilizing these local maxima points instead of the local minimum, as input to the watershed algorithm, the effective separation of the connected buildings may be achieved.

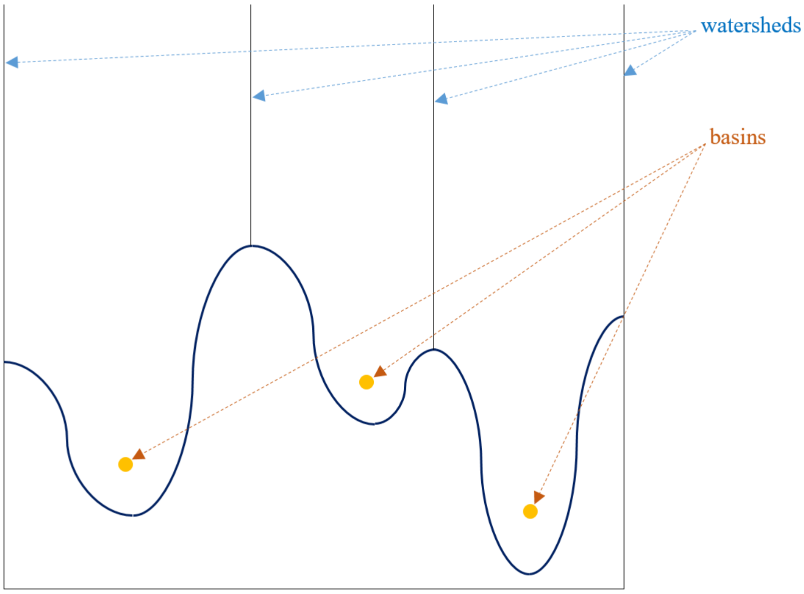


Figure 52. Watershed Segmentation – Overview.

- *Vectorization*

In the last step of the proposed methodology, the resulted binary image is vectorized. Each region of pixels sharing a common value, is converted to a vector polygon representing the respective detected building. The output of this conversion is very noisy, containing a large amount of unnecessary vertices. Thus, to overcome this drawback the Douglas-Peucker algorithm (Douglas, 1973) is utilized aiming to simplify and normalize the vector output while preserving the overall geometry. Finally, the vectorized data are exported in polygon shapefiles (shp), enabling their further use by several geospatial applications.

3.3.2.2 Experimental Results

In this section, the cloud-based software that has been developed for the implementation of the proposed methodology is presented, along with the test dataset and the achieved results.

3.3.2.2.1 Developed cloud-based software

The implementation of the proposed methodology is realized on the cloud-based workbench of Kaggle (Kaggle, 2022), in the programming language of Python (3.7), using the machine learning library of Pytorch (1.6.0) in combination with a number of other machine learning, scientific and data management libraries. As georeferenced aerial imagery is processed, the GDAL library (2.4.1) is also required.

3.3.2.2.2 Dataset

As training dataset, the Massachusetts building public dataset (Mnih, 2013) is utilized, containing 151 aerial images of 1500 × 1500 pixels each, covering roughly 340 square kilometers of the Boston area. The dataset includes mostly urban and suburban areas with buildings of different shapes and sizes (Figure 53).

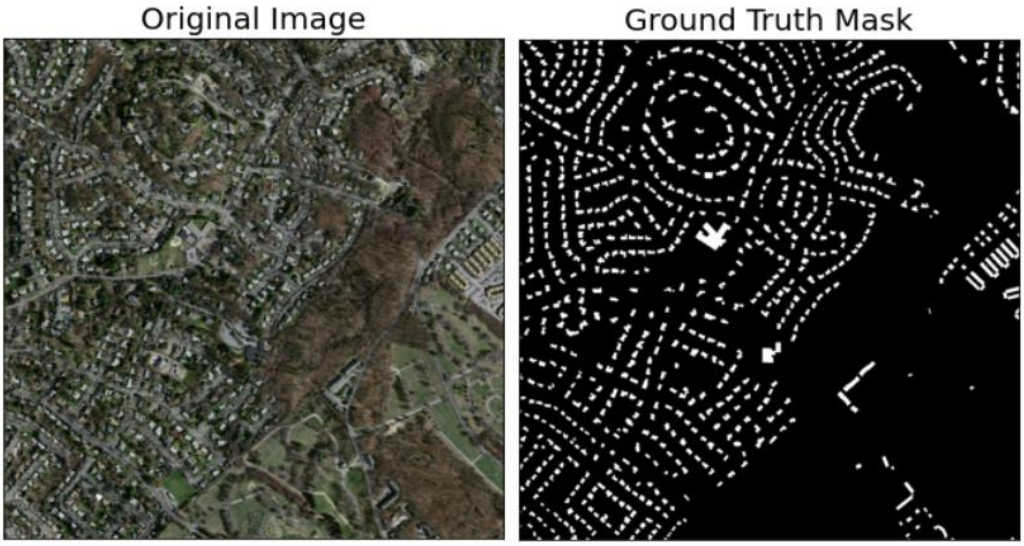


Figure 53.Orthophoto (left) and ground truth mask, illustrating a part of the studied area.

3.3.2.2.3 Pre-processing

The dataset was split into training, test and validation set, containing 137, 10 and 4 images, respectively. Each image was accompanied with a ground truth map, presenting the building and non-building areas. The ground truth maps are obtained through rasterizing the building footprints as they incur in OpenStreetMaps (OSM, 2022), while some hand-corrections were made in order the evaluations to be optimized.

As the input images are of very large size, they are divided into patches of 256 x 256 pixels. Both inputs and labels went through several augmentations, namely vertical, horizontal flips and random rotations. The outcome of these processes was fed as input to the neural network.

3.3.2.2.4 Training and Testing

For training the U-Net++ network we used 120 epochs and batch size of 16, as our dataset is of relatively small size. During training, the Adam stochastic optimizer (Kingma & Ba, 2014) with a learning rate of 2×10^{-4} and the proposed BA loss function are utilized. As activation function, the Sigmoid function is selected, as it can wield properly binary classification problems. Model training lasted about 49 minutes while testing about 3 minutes.

Figure 54 right presents the prediction masks provided through the proposed model configuration. The majority of the buildings are correctly detected while their predicted form adequately reflects their actual shape. Table 1 shows the achieved values of the evaluation metrics during the test implementation. In particular, the recall, precision, Fscore and accuracy metrics have high success rates indicating that the model provides accurate and reliable predictions. According to IoU score the predicted shape of the buildings approximates their actual shape by a percentage of 82.1%, achieving an average shape overlap of 82.1%.

Method	*Loss*	*Recall*	*Precision*	*Fscore*	*Accuracy*	*IoU*
U-NET++/BA	*0.554*	*0.915*	*0.887*	*0.901*	*0.904*	*0.821*

Table 1. Model performance using the proposed BA loss function.

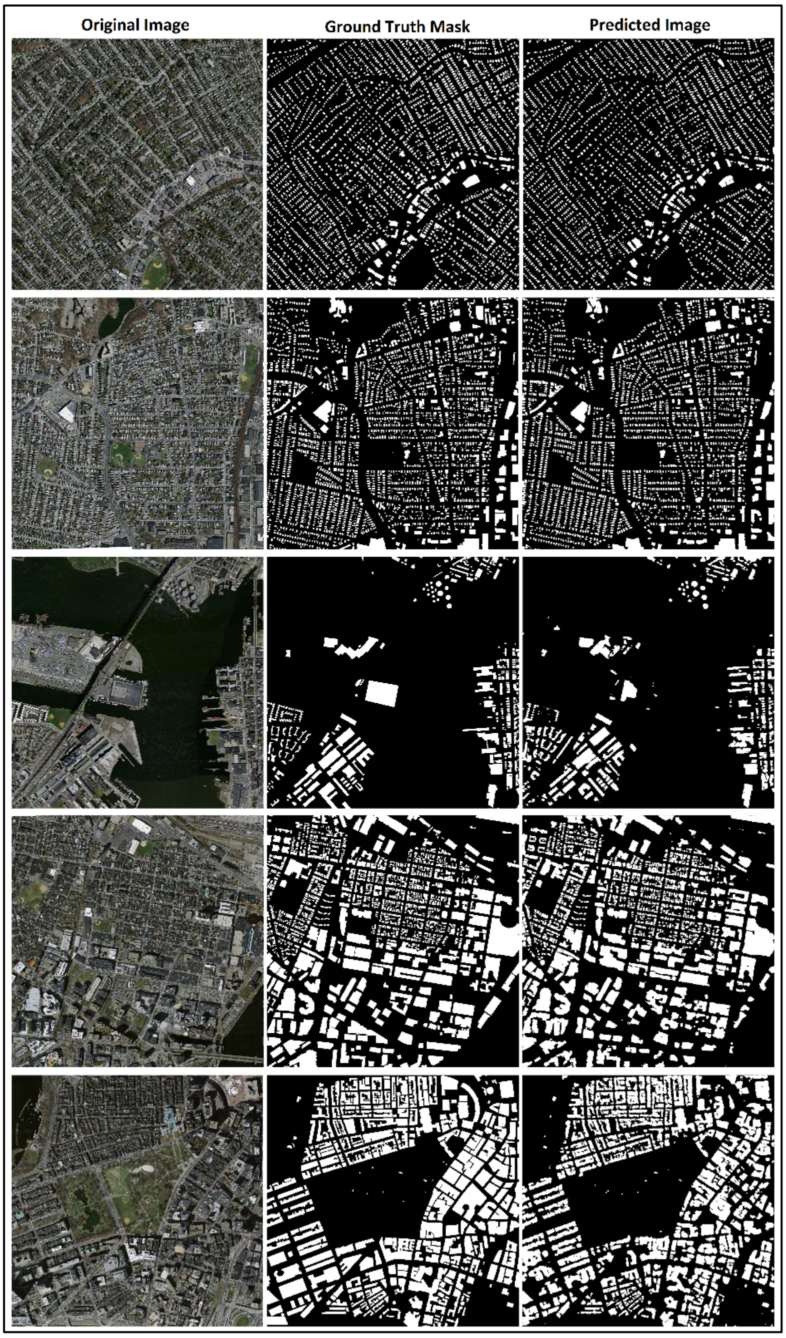


Figure 54. The original orthophotos (left column), the ground truth masks (middle column), and the predicted masks of the detected buildings (right column).

3.3.2.2.5 Post-processing

Once the predicted data are produced, the proposed post-processing procedure is applied, aiming to optimize the final outcome and extract the geo-referenced buildings outlines in vector format. First, a morphological operation of erosion followed by dilation process is applied, to remove as much noise as possible from the binary outcome of the predicted data. To proceed with noise removal a kernel of 3x3 pixels is selected, as structural element. Next, a watershed segmentation algorithm focused on local maxima is applied, aiming to separate the connected buildings blobs. As maximum distance between two separate buildings the 7.5 m is selected, thus smaller buildings to be identified as well. Finally, the binary outcome of the previous stages is vectorized and simplified through the Douglas-Peucker algorithm with a threshold of 0.7 m. The final outcome of the described procedure is presented in Figure 55.

Figure 55. Example of the detected buildings in vector format, overlaid to an orthophoto depicting the respective study area.

3.3.2.3 Evaluation of Results

In order to analyze the importance and contribution of the different components of the proposed methodology, including the selected neural network and the proposed training loss function, various combinations of these components were tested. The neural network of the classic U-Net model was adopted as baseline model in our comparisons. These models are trained and assessed utilizing the same dataset and processing platform. For the quantitative evaluations of buildings segmentation results the commonly used metrics of recall, precision, Fscore, accuracy and IoU score are selected.

Table 2 shows the performance of U-Net++ and U-Net networks utilizing either BA or BCE loss functions, consecutively. As illustrated in Table 2, the proposed model configuration that combines the U-Net++ network with the BA loss function outperforms the other combinations examined. By comparing the performance of U-Net++ with U-Net networks using the proposed BA loss function, it appears that the proposed configuration achieves improvements of approximately 1.0% (0.915 vs. 0.906), 0.8% (0.901 vs. 0.894), 0.7% (0.904 vs. 0.898) and 1.3% (0.821 vs. 0.810) in recall, Fscore, accuracy and IoU metrics, respectively. Although the improvement is not enormous, it is particularly important as it further increases the accuracy and reliability of the results.

Aiming to highlight the contribution of the proposed BA loss function for small datasets, another comparison is made between the performance of U-Net++ network with BA and BCE metrics, respectively. Table 2 shows that the U-Net++ model performs better when using the proposed BA loss function. For the four of the five metrics, namely recall, Fscore, accuracy and IoU, the utilization of the proposed BA loss achieves improvements of approximately 2.2% (0.915 vs. 0.895), 1.0% (0.901 vs. 0.892), 0.7% (0.904 vs. 0.898) and 1.6% (0.821 vs. 0.808) respectively, over the BCE loss. On the contrary, by using the BCE loss instead of BA, the precision is slightly better by 0.3% (0.890 vs. 0.887).

Method	*Loss*	*Recall*	*Precision*	*Fscore*	*Accuracy*	*IoU*
U-NET++/BA	***0.554***	***0.915***	*0.887*	***0.901***	***0.904***	***0.821***
U-NET++/BCE	*0.564*	*0.895*	*0.890*	*0.892*	*0.898*	*0.808*
U-NET/BA	*0.558*	*0.906*	*0.882*	*0.894*	*0.898*	*0.810*
U-NET/BCE	*0.563*	*0.894*	***0.893***	*0.894*	*0.899*	*0.809*

Table 2. Model performance using the proposed BA and BCE loss function.

Nevertheless, it is important to state that the use of BA leads to better results without overfitting or under-fitting the model, which is not the case with the exclusive use of BCE loss (Figure 56 & Figure **Error! Reference source not found.**57). Figure **Error! Reference source not found.**57 illustrates the under-fitting trend of the U-Net++ model that occurs when training the model for 120 epochs using the BCE loss function. To overcome this drawback, the model should be trained for more than 120 epochs. However, the more epochs the more the computational cost of the procedure. Thus, it seems that the proposed BA loss function enables the fast convergence of the model, reducing significantly the computation time and providing accurate and reliable results.

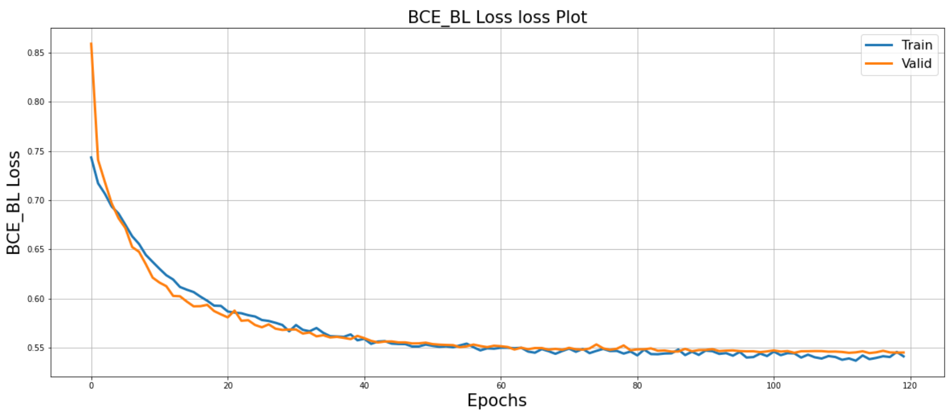


Figure 56. Model performance using the proposed BA loss function.

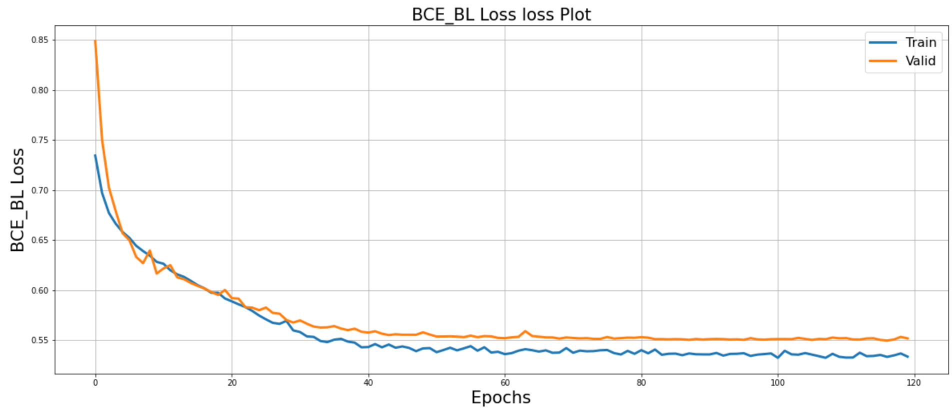


Figure 57. Model performance using BCE metric as loss function.

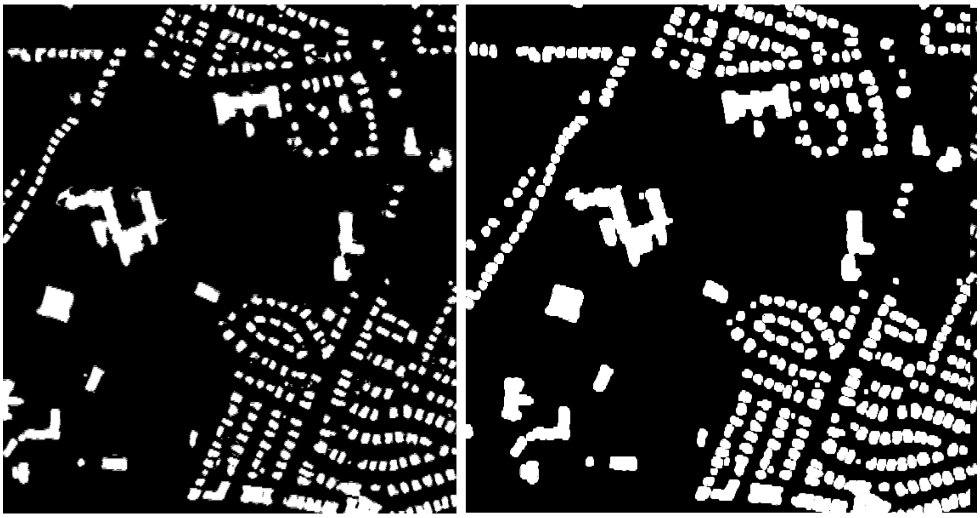


Figure 58. Part of predicted image mask (left) and the same image part after noise removal and watershed segmentation.

In addition, through the proposed post-processing procedure the majority of noise is removed and the buildings are represented as separate objects. As depicted in Figure 58, the boundaries of the buildings are presented more distinct. However, in this particular experiment the study area is covered by residential or manufacturing buildings which are sparsely distributed. This simplifies the detection and extraction of the buildings, leading to good results. As shown in Figure 59, the outlines of the buildings are correctly identified toward or very closely to their actual boundaries.

Figure 59. Example of correctly detected buildings outlines in vector format.

3.3.2.4 Concluding remarks

In Section 3.2, a deep learning methodology for the detection, extraction and vectorization of buildings outlines in sparsely urbanized areas has been presented. The U-Net++ network is examined in semantic binary segmentation of buildings outlines from geo-referenced aerial RGB imagery. To train the model, a novel Boundary-Aware (BA) loss function is proposed, reducing the required computational time through enabling the fast convergence of the model and maintaining the results reliable. As proved, the U-Net++ method has better performance than the U-Net method, utilizing the proposed model configuration. The proposed BA loss function outperforms the commonly used BCE metric without under-fitting or overfitting the model, being an important element for the fast training of models using small datasets.

Following the proposed post-processing procedure, a valuable geo-spatial outcome is provided, useful to several 2D and 3D GIS applications. Through combining these vector/polygonal outlines with height information, the 3D volumetric models of the buildings may be automatically generated. The developed methodology is highly effective in the segmentation of structured building datasets with detached buildings. However, of particular interest is the examination of its performance in more densely constructed urban areas where the buildings are adjacent to each other.

3.3.3 Discussion

Building upon the 3D reconstruction methods and strategies presented in in this Chapter, two different methodologies aiming to extract specific characteristics regarding the structure of the buildings, are presented.

The first methodology focuses on the detection and reconstruction of noisy building's roof tops using photogrammetric techniques. The developed methodology processes a dense point cloud and classify it into points sets representing either structural elements of the building's roof tops or non-roof tops elements. By excluding the last ones from the initial dataset, proceeds with the imposition of several general constrains referring to the structure and the shape of the buildings. Lastly, concludes to the partial reconstruction of a watershed surface representing the building's roof tops. The final outcome of this methodology may provide a reliable representation of the buildings roof tops removing a large volume of rooftop-level noise, nevertheless it does not constitute an easily understandable and usable product for applications such as 3D Cadastre, where the main interest relies on the explicit definition and 3D demarcation of the individual properties.

The second methodology focuses on the detection, extraction and vectorization of buildings outlines using deep learning techniques. Through this methodology the geo-referenced vector outlines of the buildings are extracted from aerial imagery. The proposed model configuration draws the attention to the boundaries of the buildings allowing their effective identification. Simultaneously, it reduces the time of the procedures, providing a fast solution for the generation of useful geospatial information. It is noted, that the developed methodology is best suited for sparsely structured urban areas, as the study area on which the model is trained is covered by residential or manufacturing buildings which are sparsely distributed. However, based on scientific claims presented in the recent literature, the developed methodology can be adapted to areas with different characteristics, after the realization of an additional training session with data representing both sparsely and densely structured urban environments. This method seems to have more prospects than the previous one, as the generated building outlines can be used as guides in the identification of the properties, especially in lack of cadastral registration basemap. However, a key disadvantage of this method is the high computational cost requirements, which leads to the further increase in the cost of cadastral procedures. Nevertheless, it is considered that with more research the results of this method can be further improved and support both 2D and 3D Cadastres.

Therefore, it seems that the utilization of aerial imagery and data-driven methods, such as those developed in the context of this Chapter, are not capable of supporting the recording of 3D cadastral objects. However, as it is illustrated in Chapter 2, the recording of 3D cadastral objects is oriented towards a more structured parametric presentation of the properties, either as simple objects/volumes in LoD1 to more complex ones in LoD4.

3.4 Conclusions

In recent literature several 3D reconstruction approaches have been proposed. The selection of the appropriate reconstruction method depends on several parameters concerning the scale, the type of the studied object or scene, the type of the initial data, the required accuracy of the final product, the available funding and so on.

Passive photogrammetric methods provide a cost-effective method for acquiring data in different scales. However, they are strongly influenced by changes in lighting conditions and the possible absence of texture, which leaves the active methods intact. Active methods such as airborne or terrestrial laser scanning, tend to be less demanding in terms of lighting conditions, but they are expensive. In addition to the use of remote sensing imagery or laser scanning data in the reconstruction processes, the utilization of images taken through low-cost devices and crowdsourcing techniques is recently promoted, reducing the costs of the overall procedure. Also, the recent development of positioning systems that incorporate information provided by different sensors has led to a reduction in dependency and problems associated with the use of GNSS as a unique way of locating. Thanks to the use of inertial navigation systems, radio signals (WiFi and Bluetooth, 3G, UWB sensors) and previously known geometric constraints for the environment (if available), it is possible to obtain reliable and fairly accurate estimations regarding the position of the mobile device used to obtain information, such as images. The level of accuracy depends on the recording system used and the operating conditions (e.g., environmental characteristics - humidity, good mobile antenna formation).

The research towards the automatic extraction and reconstruction of 3D buildings from these diverse data sources, has resulting in the development of several interesting methods that can be divided into three main categories: (i) Model-driven methods, (ii) Data-driven methods, and (iii) Hybrid methods. Model-driven or top-down approaches are based on a priori known information about the shape of the buildings. Their main advantages are the robustness in the case where the initial data are incomplete and weak, and the topologically correct output model. Parametric methods may be relatively complex, incorporating several different object libraries; or quite simple, through exploiting information of the buildings footprints and generate a volumetric representation by extruding the given footprints to a uniform height.

Data-driven or bottom-up approaches are more flexible as they do not require any prior knowledge about the building structure. The majority of the investigations included in this category, focus on extracting information regarding the geometry of the building's roof tops, in order to proceed with 3D reconstruction. The geometry of the roof can be described by a set of geometric primitives (planes, lines, etc.) which are utilized as guides toward the 3D reconstruction procedure. One of the most commonly used data sources of this category is the dense point clouds and the DSMs. The points are usually clustered into groups based on similar attributes, such as normal vectors, distance to a localized fitted plane or height similarities, and processed through methods such as: (i) plane fitting, (ii) filtering and thresholding, (iii) segmentation and region growing, and (iv) supervised classification methods. Once the points reflecting the geometry of the study buildings are determined, their detailed surface reconstruction is feasible, utilizing either combinatorial methods or implicit methods.

Recent innovations and developments in hardware and software used in photogrammetry has led to an increase in the spatial resolution of images and their products. This achievement in combination with the growth in the field of computer vision, has led to the development of several algorithms and techniques, enhancing the potentials of accurate buildings detection, extraction and reconstruction. The introduction of dense image matching algorithm enables the creation of dense point clouds or DSMs that compete precisely with expensive systems, such as LiDAR. Also, the remarkable progress in the field of computer vision, indicates that deep learning techniques may essentially improve the performance of object detection and semantic segmentation, playing a critical role in promoting the accuracy of buildings detection towards applications of automatic mapping.

Comparative studies of the existing reconstruction methods have shown that in order to achieve complete automation, remote sensing imagery and LiDAR data must be combined, exploiting the advantages of high spatial resolution and altitude accuracy, respectively. At present, it can be said safely that, for all types of objects and scenes, there is no single reconstruction technique capable of satisfying all the requirements of high geometric accuracy, portability, full automation, photo-realism and low cost as well as flexibility and efficiency. Until now, several valuable efforts have been made but there is plenty of room for further research.

Exploiting the abovementioned knowledge, two alternative approaches aiming to extract certain buildings structures and assist the 3D cadastral surveys are developed and presented. Utilizing the aforementioned knowledge, two alternative approaches are developed and presented, aiming to extract certain building structures and assist 3D cadastral surveys. As it turned out, the proposed data-driven methods are not a suitable solution for supporting 3D cadastral tasks, highlighting the model-driven methods as the solution with the most potential for this field.

Chapter 4

Three Dimensional (3D) Crowdsourcing cadastral mapping practices

During recent decades we have witnessed an overwhelming technological revolution intensively affecting the way that geospatial data are acquired, maintained, analyzed, visualized, used and disseminated. In recent years, Volunteered Geographic Information (VGI) and crowdsourcing became popular, and are described as an ever-expanding range of users that collaboratively collects geographic data (Goodchild, 2007a). The concept of crowdsourcing is very similar to VGI but consists a more targeted approach, being an act of outsourcing tasks that traditionally performed by an employee or contractor. In contrast the concept of VGI focuses on the voluntary aspect of the process. Each volunteer acts like a remote sensor (Goodchild, 2007b) by creating and sharing geographic data in a Web 2.0 community and thus, a comprehensive data source is created. Until now, the majority of data collected by the VGI-driven communities is mostly restricted to the 2D domain, enabling the generation of 2D maps. However, modern practices and requirements aim to the development of a VGI geo-data future and Internet-based automated photogrammetric solutions, in order to describe in detail and model the 3D world. Hence, the crowd and each internet-user may be defined as potential neo-photogrammetrists (Leberl, 2010).

The generation and dissemination 3D city models of the real environment is valuable for many experts as they provide useful information for a wide variety of applications, such as urban planning, 3D cadastre, risk management, navigation etc. One of the most important features in 3D city models are the buildings, since they serve as a major geospatial element in many applications such as environmental, simulation, architecture, city planning, land administration and the estimation of real estate taxes. Conventionally 3D buildings' models are produced by authoritative mapping agencies relying on aerial photogrammetry and laser scanning. Traditional photogrammetric mapping has been in the realm of industrial organizations collecting imagery from the air and developing maps and perhaps 3D information of urban spaces from these images (Leberl, 2010). These approaches may lead to detailed and accurate results but also require time, funds and experts' involvement.

The introduction of the crowd into the sensory element of data collection and photogrammetry poses additional challenges, as the data are not recorded according to photogrammetric requirements. While contemporary software can deal with difficulties like unknown and varying focal length, lighting changes, and incompatible images (images of different scale), a number of common problems remain. The selection of the appropriate methods for the management of the 3D crowdsourcing data must be conducted carefully, keeping in mind the required accuracy based on the purpose of the current application.

In this Chapter the progress related to the utilization and the perspectives of VGI and crowdsourced data in visualizing the 3D world, is presented. Then, a literature review of the current approaches concerning the introduction of crowdsourcing in 2D cadastral surveys; and, the potential of using crowdsourced data in 3D reconstruction procedures for cadastral purposes, indicating the advantages and disadvantages of this approach, are presented. Following, an investigation regarding the main parameters affecting the participation of citizens in a crowdsourcing project, is presented. The next Section concerns the exploration of the main elements that affect the quality of the geospatial data focusing on the accuracy, while in the last Section a survey regarding the most important parameters in designing applications affecting their usability, is presented.

4.1 3D Crowdsourcing in mapping applications

During the last decades research in the field of Crowdsourcing and VGI (Volunteer Geographic Information) has attracted a grown interest, resulting in the development of a large amount of 3D real world applications. One of the most successful and popular VGI projects that started in 2004 in England is the OpenStreetMap (OSM) (Figure 60 left) (OSM, 2022). Until now, there are more than 5M registered contributors, and more than 335M mapped 2D building footprints (Fan & Zipf, 2016; Bshouty et al., 2020). The positional accuracy and completeness of the collected footprints is relatively high, with a positional offset of several meters that is due the oblique distortion existing in the satellite imagery used for the building digitization (Bshouty et al., 2020). Based the positional accuracy of the buildings features, several attempts are made trying to exploit some OSM key values to generate information regarding the 3rd dimension, that is the height and the number of the floors (levels) of the buildings. Based on OSM statistics only 3% of the 505 million building footprints in OSM have the ‘height’ data key while only 4.5% use the ‘levels’ data key, mostly concentrated in Europe and North America (OSMstatistics, 2022).

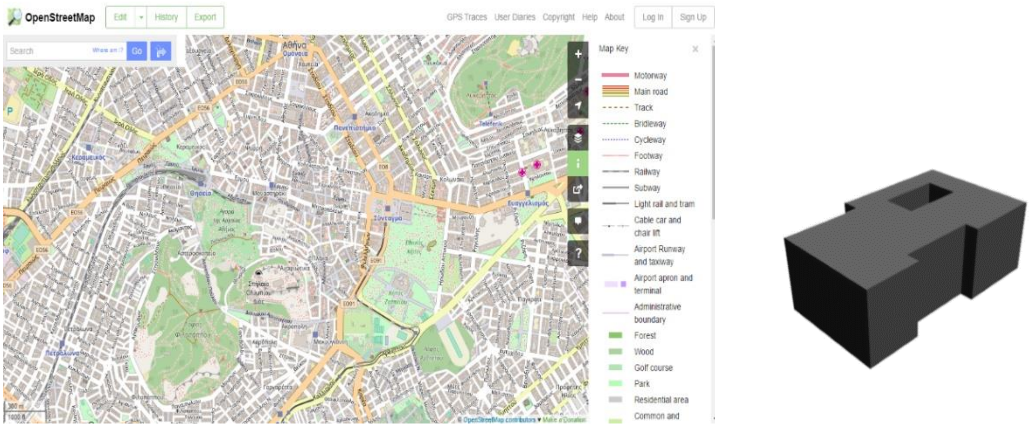


Figure 60. Representation of Open Street Map (OSM) (left); Geometrical representation of a building in CityGML LOD1 (right) (Source: Goetz & Zipf, 2012).

Research in this field has shown that OSM data has a huge potential in fulfilling the requirements of CityGML LOD1 (Gröger et al., 2008), that is block models, enabling the creation a 3D virtual world (Over et al., 2010) (Figure 60 right). Over the years several projects appeared trying to generate and visualize 3D buildings from OSM, such as OSM-3D, OSM Buildings, Glosm, OSM2World, KOSMOS Worldflier, etc. The major limitation of these projects is that the majority of buildings are only modelled at coarse level of detail. OSM-3D, created in 2008, aiming to create realistic 3D models. It is noted that OSM-3D buildings may be modelled in LOD2 if there are indications for their roof types (Figure 61). Another example of such projects is OSM Buildings that attempt to generate LoD1 building models by extruding the building footprint according to its height. Usually, the median or maximum of all elevation samples located within the building footprint or an approximate height based on the number of the floors (levels) of the building, are used.

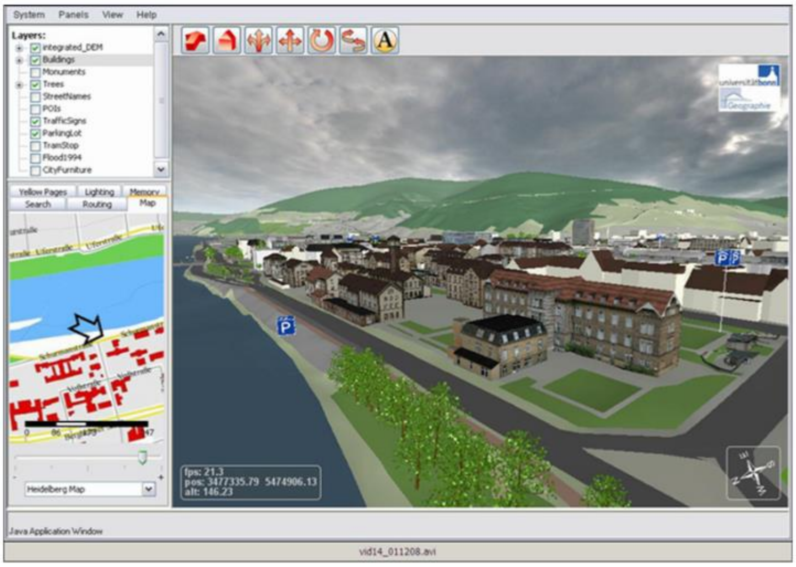


Figure 61. OSM-3D overview of Heidelberg in XNavigator (Source: Fan & Zipf, 2016).

A few years later, Goetz & Zipf (2012) presented a framework for automatic VGI-based creation of 3D building models encoded as standardized CityGML model. The basic idea is the correlation between properties and classes of OSM and CityGML, respectively. The investigation concluded that it is possible to create LOD1 and LOD2 but not LOD3 and LOD4. The development of an algorithm to automate the process and manage the incorrect input data using several assumptions, is of a great necessity for the success of the proposed framework. The integration of more detail may be conducted manually (LOD3 / LOD4) using other sources via OpenBuildingModels (OBM) (Uden & Zipf, 2013). OBM is a web-based platform for uploading and sharing entire 3D building models. More specifically, users can: (i) upload a 3D building model which is associated with a footprint in OSM, and (ii) browse, view and download an existing model in the repository. At the same time, one can add attribute information referred to the building model (Fan & Zipf, 2016). Obviously, the creation of 3D models requires a well-suited modelling software. There are several 3D graphics modelling software but different tools need different skills. Kendzi3D JOSM-plugin (Kendzi, 2022) is a widely used editor which is specialised for advanced OSM 3D-building modelling, makes it easier for the users to assemble parametric 3D models without caring about the rather complicated and cumbersome tagging itself. Such an editor could also avoid incorrect modelling and ensure topological consistency in complex 3D objects (Uden & Zipf, 2013).

The earliest and most prominent example of encouraging the crowd to generate spatial 3D information is Google 3D Warehouse launched on April 24, 2006. This shared repository contains user-generated 3D models of both geo-referenced real-world objects, such as churches or stadiums, and non-geo-referenced prototypical objects, such as trees, light posts or interior objects like furniture. Users must have a certain level of 3D modelling skill in order to voluntarily contribute (Uden & Zipf, 2013). The recent development of 3D modelling software such as SketchUp and ESRI CityEngine (Figure 62) that makes 3D editing more easy and effective leads to an increase of 3D building modelling production. Furthermore, in about 2007, Microsoft Virtual Earth and Google Earth integrated VGI and crowdsourcing techniques in their projects. 3DVIA (Virtual Earth) and Building Maker (Google Earth), provide a model kit to create buildings. Both of them exploit a set of oblique (and proprietary) birds-eye images of the same object from different perspectives, in order to derive the 3D geometry. The latter ones aim to create geo-referenced 3D building models and refer to people who do not have technical skills in 3D modelling, but still want to contribute (Fan & Zipf, 2016). Even though the abovementioned projects are based on collaboratively collected data, they are far away from been open source or open data. Hence, there are several free-to-use 3D object repositories on the internet, such as OpenSceneryX6, Archive3D7 or Shapeways8. Their contents usually lack connection to the real world but can nonetheless be useful to enrich real 3D city model visualisations (Uden & Zipf, 2013).

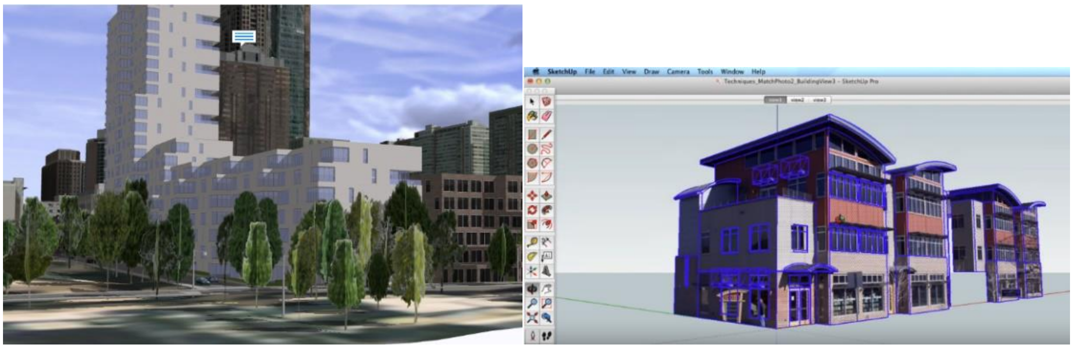


Figure 62. Examples of Parametric models creates with 3D modelling computer programs ESRI CityEngine (left) (Source: ESRI, 2017) and SketchUp (right) (Source: SketchUp, 2017).

Besides the abovementioned approaches, a different example following the use of parametric methods is proposed by Eaglin et al. (2013) through exploiting the power of mobile devices in terms of VGI and 3D reconstruction of the real world. The proposed system was based on a client-server architecture, where users may create, submit, and vote on 3D models of the inside building component. The mobile application allows users to create geometry (such as chairs, tables, etc.) through a simplified toolset and editor using parametric modelling techniques (Figure 63).

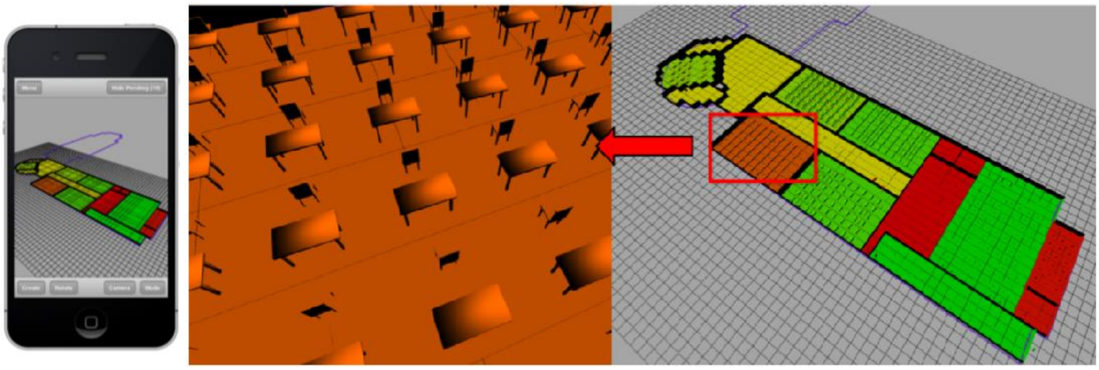


Figure 63. Mobile application for the creation, submission, and voting on 3D models of building inside components (left); Model of the first floor of an academic building with furniture (middle); Coloring corresponds to approval of the model components (red has the fewest and green the highest number of votes) (right) (Source: Eaglin et al., 2013).

A wide range of tools and algorithms is required in order to support a motivated mapper to collect the various 3D information in all levels of detail. Data collection for 3D modelling of simple building properties does not always require the use of high accuracy sensors since most data can be measured with the eye. More complex models can only be created by means of various sensors such as laser meters, terrestrial and/or aerial imagery, GPS or even terrestrial laser scanners. Many of these sensors are nowadays included in modern smartphones, transforming them into a multi-sensor-system which is pretty well-suited for crowdsourced 3D data capturing. In the future, further sensors like barometers, stereo cameras such as Microsoft Kinect (Elgan, 2022) and maybe also laser meters and little laser scanners will possibly be included into smartphones, making them even more all-round tools for 3D-VGI. The valuable contribution of smart devices in buildings height estimation for public domain 3D building models, is an active research field. Bshouty et al. (2020) investigate the potential use of the smartphone camera sensor, aiming to provide information regarding the building height. They proposed the utilization of a single photograph captured by citizens via smartphones or tablets, together with the existing mapped OSM vector data to precisely calculate the photographed building height. This value is automatically inserted into the OSM database, enabling the creation of fundamental building models at LoD1. However, it should be noted that such procedures that treat altitude information need special attention as the DTM used in OSM is based on the authoritative produced Shuttle Radar Topography Mission (SRTM) infrastructure, despite the fact that OSMs' contributors actively collect their geospatial location, as in GNSS trajectories (Bshouty et al., 2020).

Furthermore, many amateur digital cameras (including those on smartphones) have a cheap, consumer-grade single-frequency GNSS receiver, and sometimes the GNSS coordinate at the time of taking the picture is stored as metadata in the image's EXIF header. These coordinates, sometimes referred to as geo-tags, are currently not available for the majority of images and they are not accurate enough to be used directly – errors in some cases exceed 10 m. But, just like the approximate focal length that is also often part of the metadata, they are good enough as initial values, and can constrain the problem sufficiently to overcome some positional problems (Hartmann et al., 2016). Camera pose estimation and 3D reconstruction from arbitrary, uncontrolled images has reached a certain maturity, as evidenced by several open-source and commercial software packages (e.g., Bundler, VisualSFM, Pix4D, Acute3D, Agisoft PhotoScan). Nevertheless, a number of important open problems remain, which is the reason that crowdsourced photogrammetry has not yet been widely adopted for surveying purposes. The main issues in our view are: (i) more often the models are incomplete and show only some of the sides of a building or scene; (ii) repetitive structures and symmetries lead to incorrect correspondences and gross errors (e.g., missing parts) of the 3D models; and, (iii) even if several useful parts of a larger scene have been reconstructed correctly, the models are not geo-referenced with appropriate accuracy.

In order to overcome the abovementioned problems, Hartmann et al. (2016) proposed a method for the creation of geo-referenced 3D models using images from Flickr, which has been the major data source for crowdsourced photogrammetry (Figure 64). As a first step, the dataset divided into smaller clusters, using VocMath method (Havlena & Schindler, 2014), which provide the set of images from each camera pose. The small, clean clusters are individually reconstructed using a SfM software (Bundler) (Snavely et al., 2008). Each of these models represents a part of the same landmark. The GNSS coordinates from the EXIF headers of the images are exploited to perform a coarse absolute orientation. For the absolute orientation between the partial 3D models, Hartmann et al. (2016) proposed to go back to the models and find corresponding 3D structure points for a better alignment. The point-to-point correspondences identified using the standard SIFT algorithm. Finally, the geo-referenced 3D model derived after a bundle adjustment, so as to fuse all available information. Also, similar research has been performed over time (Hadjiprocopis et al., 2014; Somogyi et al., 2016).

Figure 64. Reconstruction from smart phone images (left), Dense point cloud of the Parliament building after reconstruction from images (right) (Source: Somogyi et al., 2016).

Jeong & Kim (2016) proposed a planar fitting-based semi-automatic reconstruction process using smart devices, such as smartphones. The proposed methodology is developed as a mobile application for Android, and requires from user to obtain two images of the target building from two different perspectives, so each one of them may display a different side of the building and have a sufficient overlapping part. After the selection of the boundaries of the Region Of Interest (ROI) on the mobile device screen from the user, the creation of the 3D reconstruction is performed by means of the estimation of 3D surfaces function for each building side. Following, the two resulting surfaces are adapted to both surfaces of a cube. This stage is necessary to reduce errors due to some erroneous correspondences and the angular errors introduced in the process.

Zhang et al. (2016) suggests a solution to complete building reconstruction of both rooftops and façades by combining airborne LiDAR point clouds and ground image point clouds generated from smartphone images, using region growing method (Segmentation based Method). First, the smartphone images are clustered by GPS data obtained from image metadata (EXIF data). Every building is reconstructed by SfM and PMVS algorithms from a clustered smartphone image set (Furukawa & Ponce, 2010; Furukawa & Hernández, 2015). The corresponding LiDAR point cloud is extracted by using the GPS data and the image pointing information obtained from the clustered image set. Building LiDAR points are segmented to possibly different individual buildings after processing by a region-growing algorithm on the building point class. Following this stage, two forms of top view 2D outlines of target building are respectively extracted from LiDAR point cloud and ground image point cloud. In order to accurately integrate the LiDAR point cloud and ground image point cloud, they adopt the Coherent Drift Point (CDP) algorithm to match building outlines extracted respectively from LiDAR point cloud and ground image point cloud. The proposed methodology is applied to one building at a time. In the future, it is expected to be applied on a larger scale.

In the literature, there are several commercial or freely available solutions, concerning a wide range of applications. A really successful mapping mobile application for both IOS and Android mobile devices is MagicPlan (MagicPlan, 2022). The user can measure room dimensions in real-time, capturing 3D information. MagicPlan lets the user create dimensioned floor plans without actively measuring or drawing through innovative algorithms and Augmented Reality technology. To estimate room measurements, the user must interactively mark floor corners in an augmented reality view. While MagicPlan algorithms are proprietary and unpublished, they can estimate and use the height of the observer, i.e., the camera of the mobile device, and the tilt in order to estimate the scene depth. Thus, a coherent floor plan is created, depicting all the appropriate geometric data, and it can be used for the creation of the corresponding 3D model of the building space using a data model such as CityGML, which has been designed for defining and exchanging 3D urban information.

Furthermore, it is worth mentioning that the 3D reconstruction of buildings from terrestrial photographs that traditionally is accomplished using complex and expensive photogrammetric software; may be also implemented by freely available 3D modelling software, like Autodesk 123D Catch or My3DScanner, offering an alternative for this task.

4.2 Crowdsourcing in land administration

Introducing crowdsourcing in land administration procedures (Basiouka & Potsiou, 2012a; b; Keenja et al., 2012; McLaren, 2012; Basiouka & Potsiou, 2014) has caused a lot of discussion in terms of data quality, privacy concern and the achieved accuracy. Data quality has many dimensions such as absolute and relative geometric accuracy, topological correctness, accuracy of metadata and of course the legal dimension. Data collected by crowdsourcing may not meet always all those levels of accuracy. However, the basic question is the identification of the required quality of the data according to the purpose for which data are collected (fit-for-purpose approach). Fit-for-purpose means that the land administration systems – and especially the underlying spatial framework of large scale mapping – should be designed for the purpose of improving the management of current land issues within a specific country or region – rather than simply following more advanced technical standards regardless the cost and time delays for the completion of the project (Enemark et al., 2014). With the advent of social media, crowdsourced technology and imagery available on the internet, there is an opportunity for establishing land administration capacity in places that previously could not afford such systems, and to provide transparent land administration services in places where corruption and inefficiency is endemic (Adlington, 2011). In recent literature, there are many uses of crowdsourcing in map production and updating, for the management of natural disasters, the identification and recording of illegal buildings, identification of property boundaries in urban/suburban and rural areas, identification of problems in the infrastructure, determination of toponyms, updating of land cover polygons and recording of archaeological sites. Until today, there have been many studies exploring the potential use of crowdsourcing and VGI in the context of 2D cadastral systems, while their introduction for the development of 3D cadastral systems is newly emerging.

4.2.1 Previous research on 2D cadastral surveys

During recent decades we have witnessed an overwhelming technological revolution intensively affecting the way that geospatial data are acquired, maintained, analyzed, visualized, used and disseminated. Information and Communication Technology (ICT), low-cost equipment, crowdsourcing techniques, mobile services (m-services), web services and open source software (OSS) introduce a new era for cadastral surveys, minimizing the financial costs as well as the time required to perform field surveys.

In 2011, McLaren (2011) having ascertained the rapid expansion of smartphones explores the potential utilization of crowdsourcing in order to secure the tenure gap through establishing a partnership between land professionals and citizens. From this research emerged that only the 25% of land parcels are formally registered, living the rest 75% at risk. Based on these findings the universal trend has been towards a Public Participation Geographic Information System which “is a field of research that, among other things, focuses on the use of GIS by non-experts and occasional users” (Haklay & Tobón, 2003).

Impelled by this research Keenja et al. (2012) explored the perception of land professionals and specifically of the Netherlands Kadaster staff members, regarding crowdsourcing in land administration. The Q-methodology is applied utilizing participants from different parts of the Dutch Kadaster. Some believe that the government does not always use the best technology: “the technology that government adopt might be the cheapest and after some time it is no longer suitable for use and needs to be changed". They all agree that it is risky for cadastre to provide all the information for free, but at the same time they argue that all types of new technology could enter the cadastre without omitting modern technological achievements such as mobile devices. However, the prevailing view is that citizens are capable of using the right information at the right time for their own development supporting the integration of VGI and crowdsourcing in land administration procedures (Keenja et al., 2012).

The applicability of crowdsourced geospatial information to real cadastral data, as tested in New Zealand Cadastre (Clouston, 2015) and in Greece (Basiouka & Potsiou, 2012a), lead to promising results. Clouston (2015), presents an interesting investigation focusing on the connection between the opinion and behaviors of users, data producers and official mapping agencies in the cadastral structure of New Zealand. The author conclude that crowdsourced data can provide advances in data collection and maintenance processes provided that users, data producers and administrators change their perception regarding crowdsourcing and support it.

Basiouka & Potsiou (2012a) carried out the first practical cadastral mapping experiment in Greece through creating draft cadastral maps utilizing crowdsourcing techniques and a handheld GPS (Figure 65). They compared this procedure with the traditional cadastral survey procedure which is distinguished by errors concerning the location, the shape and the boundaries of the recorded land parcels. The main objective is to provide an alternative solution in order to correct the gross errors as well as to minimize the time and cost of the traditional procedures, especially in rural areas. They conclude that geometric errors included in the traditional cadastral procedure may be corrected within a small time period, which is very important as these problems in the cadastral surveys were blocking the market for more than 12 years. The participation was enormous and time was eliminated dramatically. Volunteers' were willing to participate, answer the questions and get involved in the experiment proving that the proposed crowdsourced approach had many potentials. Authors also stated that the handheld GPS will soon be replaced by smartphones and thus new applications will be created to serve these needs.

Figure 65. The Volunteers at the Rural Area (Source: Basiouka & Potsiou, 2012a).

With the extensive use of smartphones crowdsourcing is bound to mobile devices driving several investigations to examine the potential of mobile applications in cooperation with an accurate orthophoto as basemap, for the implementation of cadastral surveys. The introduction of crowdsourcing technology in cadastral surveys has aroused several concerns regarding the achieved data quality and geometric accuracy, as well as about the decreasing role of the surveyors. However, later on discussions in this field uncovered promising potentials for the development of a "fit-for-purpose" approach always under the supervision of a professional surveyor. Their main objective is to evaluate the reliability, the achieved geometric accuracy, and the usability of such procedure. In Mourafetis et al. (2015) the potential adoption of mobile devices for the compilation of accurate, assured, and authoritative cadastres such as the Hellenic Cadastre, was investigated. A newly developed ESRI's ArcGIS online application 'LADM in the Cloud', available for IOS and Android smartphones, is selected as data capturing tool while a recent orthophoto of the studied areas is used as the basemap (Figure 66). Once the right holders locate their property on the basemap they may digitize its boundary by tapping it on the mobile phone's screen. As turned out, the achieved accuracies using the GPS sensor of mobile phones are high in urban areas, due to the dense network of antennas while minor corrections regarding the position of the property boundaries on the basemap can also be achieved by moving the cursor on mobile phone's screen to the right estimated position by the user. Also, by using the selected mobile application, all the personal and geometric information can be saved in the cloud where can be secured (Celt et al., 2019).

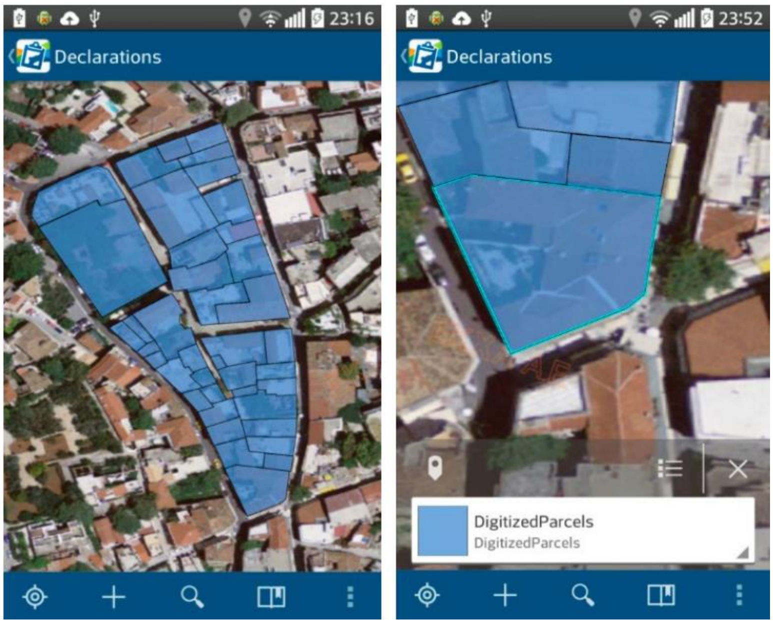


Figure 66. Digitized crowdsourced cadastral maps in urban areas using the ESRI's ArcGIS online application 'LADM in the Cloud' (Source: Mourafetis et al., 2015).

This hybrid approach was tested for urban, suburban and rural areas (Figures 67). Beyond the commercial mobile application an open source application for Android mobile services, named BoundGeometry, was developed to support the users/right holders with additional geometric tools for the determination of the parcel boundaries if they are not shown, or clearly recognized, on the basemap or in the field (e.g., due to vegetation, or the hidden parts on the orthophoto, or legal boundaries not demarcated in the field) (Figures 68). The BoundGeometry application operates complementarily to the Collector for ArcGIS to overcome the difficulties of determining non-visible boundary corners (Gkeli et al, 2016; Apostolopoulos et al., 2018).

Figure 67. Digitized crowdsourced parcels in urban areas (Source: Gkeli et al., 2016).

(a)

(b)

Figure 68. Usage examples of the BoundGeometry application for the digitization of hidden boundary corners in (a) urban and (b) suburban areas (Source: Gkeli et al., 2016).

Similar attempts, encouraging the right holders to collect and submit geometric and descriptive data regarding their properties, was initiated in 2018 during the nation-wide cadastral project in Romania (Potsiou et al., 2018; Potsiou et al., 2020). A first attempt begun through studying the formal cadastral procedure applied in the European countries of Greece and Romania, investigating their current stage of progress, and assessing the level of participation that the right holders have in the current procedures. It is highlighted that both projects began with a series of pilot participatory projects where right holders are asked to identify and locate their land parcels on a recent orthophotos. Based on these findings they propose a more fit-for-purpose approach utilizing crowdsourcing, aiming to develop a modern process that can successfully meet the deadlines timely, and provide an accurate, assured and authoritative final product. For this investigation three case studies are held in urban, rural and suburban areas for both countries, utilizing both the Esri's Collector commercial application and an open-source MapIT collector application (Figure 69), in order to proceed with the registration process. Therefore, they compared the positional accuracy of the collected crowdsourced data with respect to the data collected by experts. It turned out that the achieved positional accuracy was about 0.4 m for urban and 1.0 m for rural areas. These results seem to satisfy the cadastral requirements of both countries, enhancing the potential of exploiting crowdsourced data in the initial phases of the cadastral formal procedures.

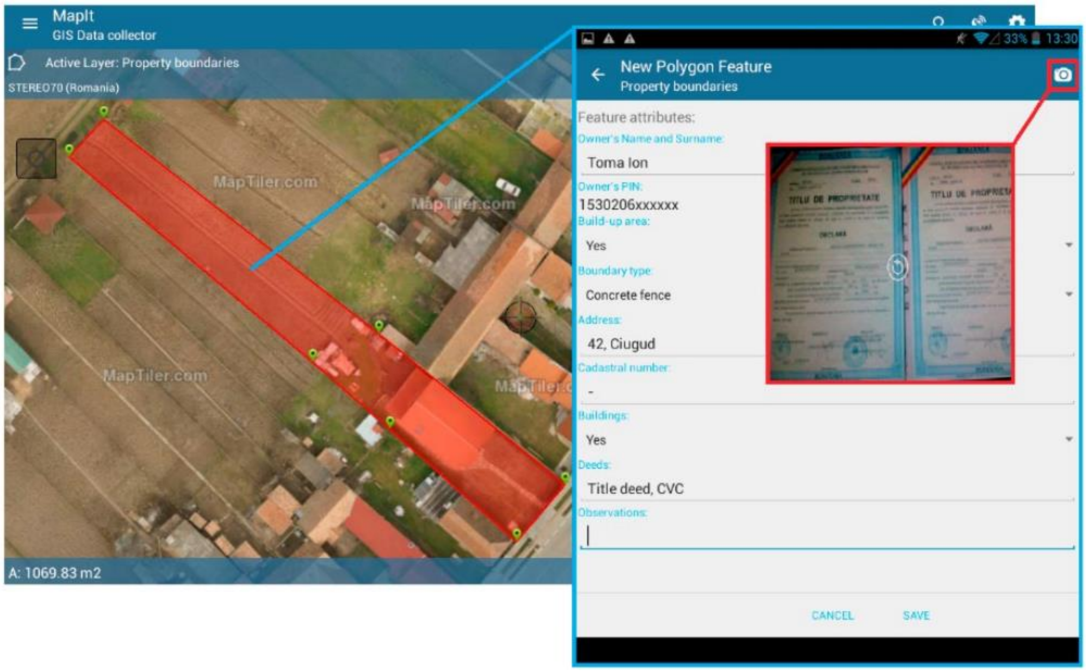


Figure 69. Interface of Map IT application for parcel data collection used in Romania – example of uploading a deed (Source: Potsiou et al., 2020).

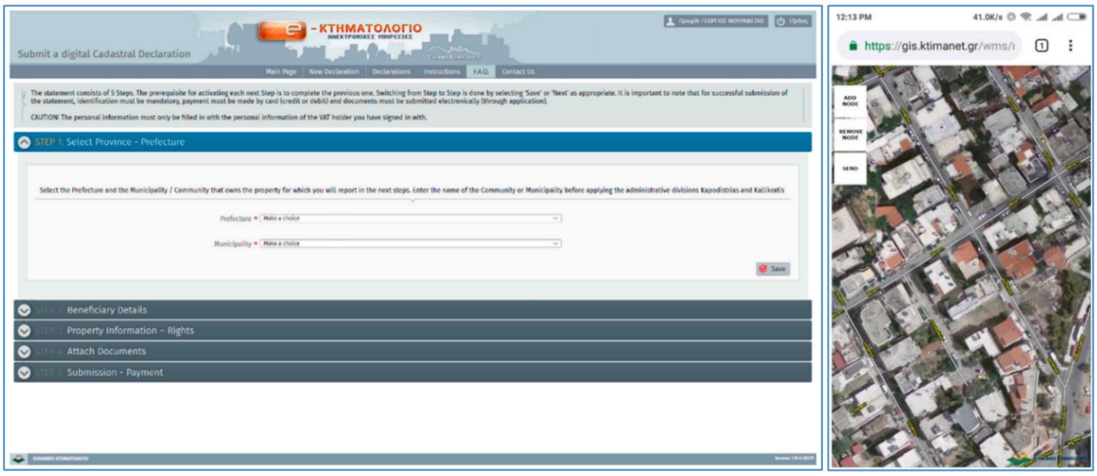


Figure 70. Web application's user interface, (left) defining the five steps for declaring a property right and, (right) tracking user position and gradually creates the parcel's boundary (Source: Mourafetis & Potsiou, 2020).

Remaining in the Greek territory, Mourafetis & Potsiou (2020) present a system architecture and IT services implemented to support the official procedure of Hellenic Cadastre property rights declaration. As already have been mentioned, the cadastral surveys in Greece are participatory with right holders to have an active role in the identification and declaration of the land parcels on which they have rights on and submit all the required legal documents proving these rights. For this purpose, a web page and a mobile application are utilized. The e-declaration process is conducted mainly through the developed web application, where the user may insert all the necessary cadastral information and declare the boundaries of the declared property (Figure 70). In cases that the users do not agree with the draft predefined land parcel, they can either edit the vertices of the predefined land parcel boundary or digitize a totally new land parcel. This process may be implemented through a web application for GPS enabled mobile devices. The right holders can access this web application and use it to record the land parcel boundaries of interest, by moving towards the physical boundaries of their property in the field (Figure 70). The proposed approach was considered a big success as the services raised the percentage of digital data submissions from below 1% to approximately 33%.

Other researches explore the potential integration of international standardization models, such as LADM, in crowdsourcing cadastral. Jones et al. (2017) present a low cost LADM-based approach for the implementation of a post conflict cadastre in Colombia utilizing modern GIS technology. The main challenge to be addressed is the informality of property in rural areas where increases the need for acceleration of data acquisition and management processes. The main pillar of the proposed methodology is the active cooperation between farmers/property owners and grassroot surveyors for data acquisition. An orthophoto of the area is utilized for the identification and determination of the boundaries of each property. The mobile application of Esri's Collector App in combination with the Trimble R1GPS device, connected via Bluetooth, is used for the collection of the spatial and administrative data (Figure 71). This handheld GPS device collects coordinates with a sub-meter accuracy. Thus, the declared boundaries have an intrinsic accuracy of about one meter. Furthermore, in a village meeting, the community members gather to see and discuss all the collected data on a map, as well as all the potential disputes, overlaps and 'gaps' in the surveyed area. The authors conclude that the proposed methodology is affordable, fast and may successfully implement a nationwide land administration within 7 years. It is also noted that such a methodology is reliable as the main focus is to settle a trust link between land and people (Jones et al., 2017).

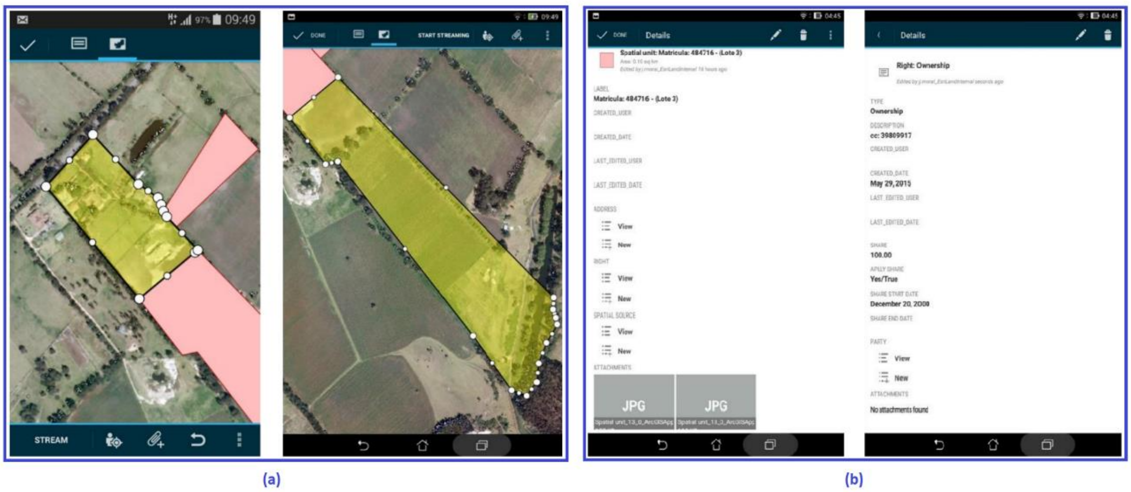


Figure 71. (a) The digitized land parcels through Esri's Collector App. (b) Esri's Collector App interface for the collection of the administrative data (Source: Jones et al., 2017).

Molendijk et al. (2018) presents a similar LADM-based methodology for the field data collection and data handling aiming to create an overview of all people to land relationships in departments of Colombia. Colombia is a country that has civil conflicts over land ownership and thus the mapping and management of the current disputes and overlapping claims is crucial. The main objective of this experiment is to speed up the cadastral surveys and the first registration process in the economies in transition for the implementation of a comprehensive Agrarian Reform. Esri's Collector App together with Trimble R2GPS device were utilized to proceed with the pilot cases. An elementary LADM-based database schema has been designed for this purpose. It is noted that the R2 has a "quality antenna" for the reception of weak GNSS signals and the reception of the required correction signals. With this configuration, a sub-meter accuracy for the observed points may be provided. Such implementation makes possible the Peace Agreements in the country and strengthens the maintenance of the population's confidence in the peace processes. The focus on rural land ownership brings with it its historical importance. In Colombia, the relationship of rural land titling is a challenge when it is estimated that around 60% of rural land parcels do not have a legal cadastral map of land holders (Molendijk et al., 2018).

4.2.2 Potentials for modelling of 3D cadastral objects

Practical experience has demonstrated the significant benefits in crowdsourcing geodetic measurement from multiple organisations (Haasdyk & Roberts, 2013). Web-based and mobile-based crowdsourcing solutions, have already been used in developing 2D cadastral surveying procedures in order to minimize the time and cost of the required surveys (Basiouka & Potsiou, 2014; 2015; 2016; Basiouka, 2015; Mourafetis et al., 2015; Apostolopoulos et al., 2018; Cetl et al., 2019; Potsiou et al, 2020; Mourafetis & Potsiou, 2020). 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 existing 2D experience should be exploited in 3D cadastral surveys, providing a fit-for-purpose solution for the initial implementation of reliable 3D Cadastres.

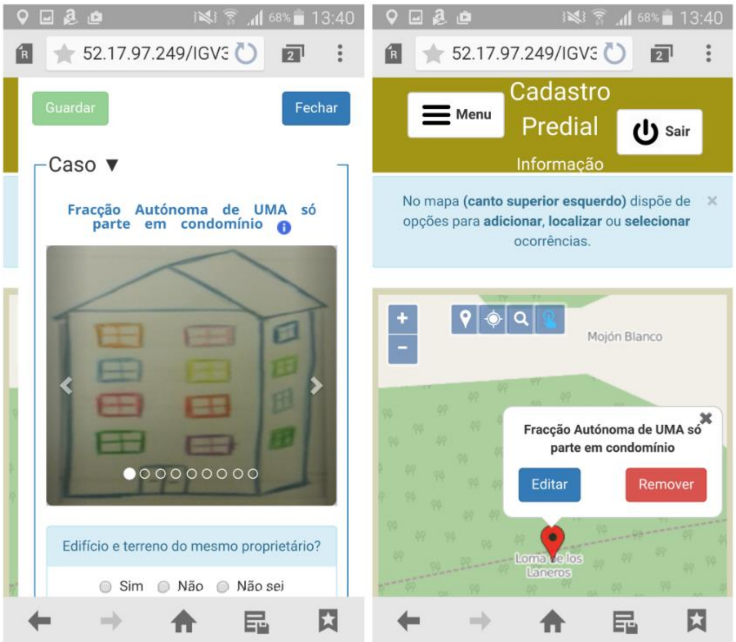


Figure 72. Example of the web-based crowdsourced application - Mobile Usage (Source: Ellul et al, 2016).

The discussion on the potential use of VGI and crowdsourced data for the compilation of 3D cadastral surveys and how to exploit right holders in order to collect the required information for the transition from a 2D cadastre into a 3D cadastre has initially started in 2015. Vučić et al. (2015) proposed a LADM-based crowdsourced solution for 3D cadastral data acquitision. A mobile device is used for the delivery of the property height, reference point and surface relation. By combining the inserted data with already existing 2D (official) information regarding the partition of the real property, the establishment of a part of the 3D cadastre and its visualization is possible. This attempt may constitute a promising approach aiming to upgrade a pre-existing 2D cadastre into a 3D cadastre. In 2016, an interesting approach is proposed by (Ellul et al, 2016) aiming to investigate the necessity of 3D cadastral surveys for a better representation of the 3D rights. As the boundaries of 3D property units are better known by their own occupants, crowdsourcing techniques seemed to be the best solution in order to capture the complex ownership cases that may distinguish any property. They proposed the development of a web-based crowdsourced application for the identification of the several land

and property ownership situations through a set of different sketches describing the potential alternative 3D ownership situations in Coimbra. It is noted that the developed web-based application may also be opened from a mobile phone's browser, allowing the implementation of the required procedures from different platforms (Figure 72). The contributors are asked to select their situation from several groups presenting different types of land ownership, sketched by the research team. This first attempt received positive feedback from Coimbra Municipality, however there are still several aspects of the proposed approach that need to be further investigated.

Although these studies do not lead to the development of 3D proprietary models, they constitute a trigger for the further investigation of the potential use of crowdsourced data for this purpose. Occasionally, several different research approaches aim at the partial or fully 3D reconstruction of buildings utilizing crowdsourced data are proposed (Elgan, 2022; Hartmann et al., 2016; Jeong & Kim, 2016; Zhang et al., 2016; Bshouty et al., 2020). These investigations concluded that the use of crowdsourced data may lead to satisfactory results, constituting an important part of the 3D reconstruction. Nevertheless, it is obvious that data collected through VGI and crowdsourcing contain noise and occlusions, as the data are collected by non-professionals; so photogrammetric building reconstruction may be difficult using exclusively these row data. The presence of occlusions requires sophisticated techniques and algorithms for data processing, and may thus lead to erroneous reconstructions. As extensively described in Chapter 2, the implementation of Data-driven techniques and algorithms for the development of 3D models for cadastral purposes (3D cadastre) has especially high computational costs in order the imported errors to be reduced, as much as possible. However, the 3D cadastre aims at preserving property rights, without being interested in architectural details of property geometry. Thus, the key elements are the volumes of the buildings (in LOD1 or LOD2), so that the individual properties can be correctly registered. For this reason, the use of Model-driven approaches may be preferable, since they are characterized by higher stability, maintenance of the topology, while offering an easy way of 3D reconstruction which can be adopted by ordinary citizens without specific photogrammetric skills (Figure 73).

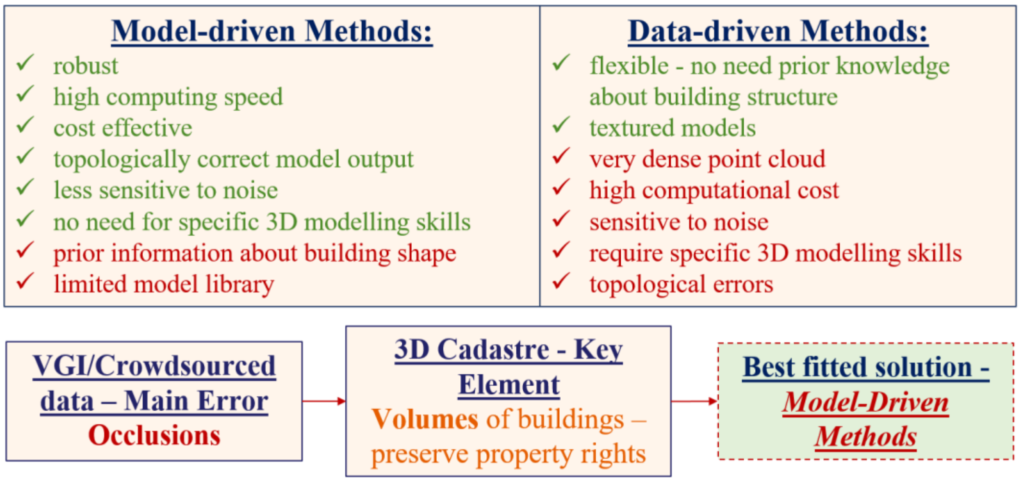


Figure 73. Advantages and the disadvantages of model-driven and data-driven methods - logical path of selecting the best fitted solution for 3D Cadastres.

4.3 Introducing Crowdsourced data into Authoritative Databases

4.3.1 Motivation for Participation and increased Public Willingness

One of the most important parameters affecting the success of any crowdsourcing application is the productivity of the participants. Until now, there have been several investigations attempting to highlight the main incentives of the participants, and attempting to engage them and maintain their willingness to stay active through the overall process (Nov, 2007; Coleman et al., 2009; Coleman, 2010; Basiouka & Potsiou, 2014). The research on participants' inceptives originates in the 1970s, while during years several studies were conducted investigating the potential integration of volunteerism in different scientific fields and applications. These studies may be divided in three (3) main categories: (i) general, (ii) GIS-based and (iii) targeted in specific geographic applications (Basiouka, 2015).

With the introduction of VGI in 2007 by Goodchild (2007a; b), a first attempt regarding the identification of the main motives of volunteers manipulating Geographic Information was presented. Based on this approach, motives are created and formed based on two key factors: (i) self-promotion and, (ii) personal satisfaction. By achieving a higher level of empowerment and satisfaction may affect the citizens' opinion for participating in a crowdsourced or VGI project such as OSM (Tulloch, 2008; Basiouka, 2015).

A different approach is presented by Coleman et al. (2009) dividing participants into five categories, that can be distinguished by either competence or accountability, based on their knowledge, capabilities and background, ranging from neophytes through to expert authorities (Figure 74). However, it is noted that this is more complicated as an individual may belong in different categories for different contributions. In a later research, Coleman et al. (2010) posed a list of factors affecting participants' behavior, dividing them into positive/constructive and negative factors. The positive factors, include altruism, professional or personal interest, intellectual stimulation, protection of a personal investment, social reward, personal reputation, self-expression opportunity and pride of place. Furthermore, the negative factors include mischief, social, economic or political agendas and malice/criminal intent.

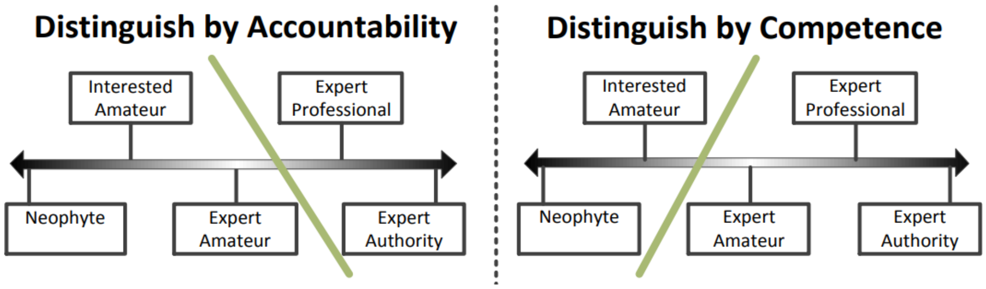


Figure 74. Approaches differentiating the various types of contributors (Source: Coleman et al., 2009).

The engagement and recruitment of the participants in a crowdsourced project is another issue addressed in the current literature. Several approaches have been proposed towards public recruitment, including the method of gamification (Apostolopoulos et al., 2018), incentivizing participants with various monetary or other rewards (Brown & Kyttä, 2014) or even with advertising through flyers and social channels such as Facebook (Sirbu et al., 2015). An interesting example of gamification strategies is presented by Apostolopoulos et al. (2018). In order to support and motivate volunteers to collect information, they created an application utilizing Esri's ArcGIS Viewer for Flex (Figure 75 left) where the user/volunteer could see how many properties have been digitized, and each user/volunteer may check how many and where are the properties which he/she has digitized by entering his/hers tax code in the search tool (Figure 75 right). Through this process each user/volunteer participates in an award process.

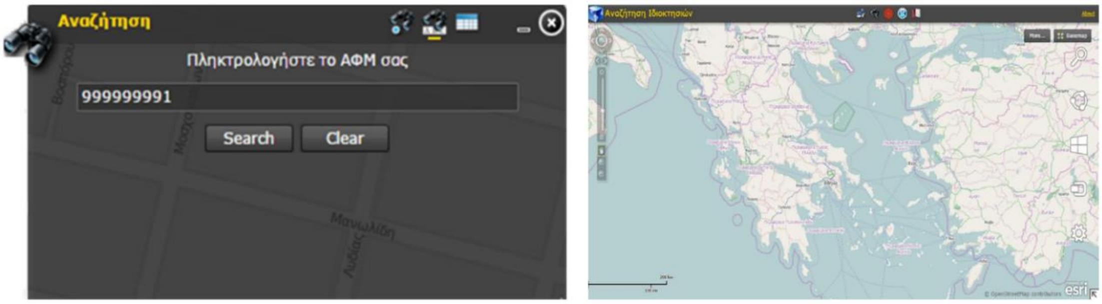


Figure 75. Screen window with the tax code number of the volunteer (left) and a map reply at the Search tool.

Through proper briefing of the public about the benefits of a crowdsourcing project, awareness may be raised, encouraging citizens to join the project. However, the effectiveness of a crowdsourcing framework depends heavily on 'finding the balance in which for the non-professional participants the operation of collecting and contributing data is not too complex in a way that might impair the quality of the data; but on the other hand, making sure that the contributor is motivated – intellectually and practically – will benefit the processes.' (Cetl et al., 2019).

4.3.2 Data Quality

Data quality is an often a debatable topic in the research community that still remains a valid concern (Goodchild, 2008b). The quality of the geospatial crowdsourced data is determined by several factors including the choice, location, skills and tools (Clouston, 2015). In ISO 8402 (1994), quality is defined as "the totality of characteristics of an entity that bear upon its ability to satisfy stated and implied needs". Data quality is often referred as data fitness when describing geospatial data, arguing that the product quality depends directly on the intended application. In this sense, data quality or data fitness may be considered acceptable if data are fit-for-purpose.

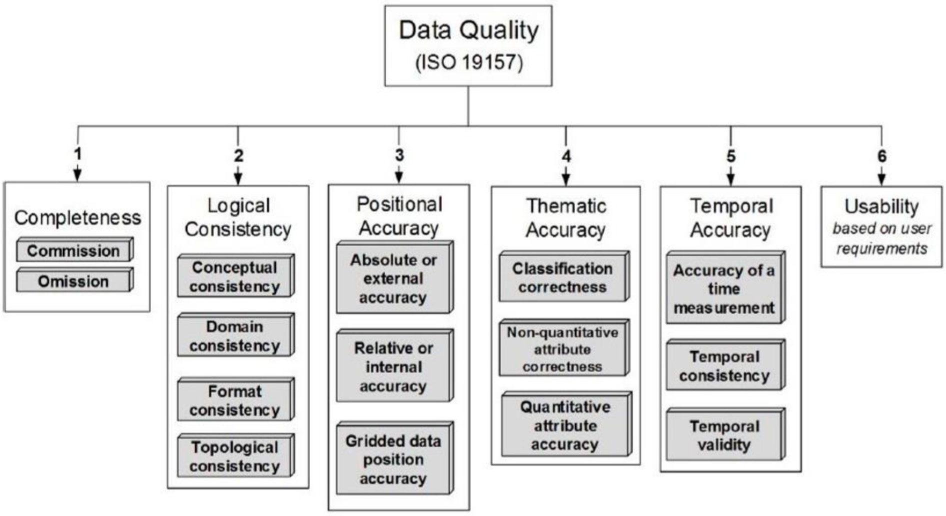


Figure 76. Data quality descriptors based on INSPIRE technical guidelines - ISO 19157 (Geographic Information Data Quality). (Source: https://inspire.ec.europa.eu/sites/default/files/presentations/Docan_INSPIRE_2017_Print.pdf)

Although data quality has several different aspects, it may be considered as a value with two broad perspectives - the internal and the external (Cetl et al., 2019). The internal perspective is based on the a priori requirements as presented by the producers and providers, while the external perspective is referred to the necessary requirements for reusing the data. Thus, data quality or fitness-for-purpose may be described and evaluated by examining some quality criteria that determine whether or not the produced data is compatible with the data product specification. Occasionally, various standards have been proposed, in an attempt to define the most appropriate quality descriptors for the evaluation of data quality. The ISO 19157 (2013) standard (Figure 76), describes spatial data quality through 21 quality elements which belong to 6 different categories: completeness, logical consistency, thematic accuracy, temporal quality, positional accuracy, and usability.

Goodchild & Li (2012), distinguished three different approaches in order to assure geospatial data quality, as follows (Figure 77):

- The crowdsourcing approach argue that data may be more accurate if a large group of people agree on it. Information based on a single individual's observation does not have the same impact.
- The social approach based on the fact that trusted users or administrators, may check the inserted new data in order to minimize errors.
- The geographic approach based on the principle that geographic data may be checked against some rules, even automatically.

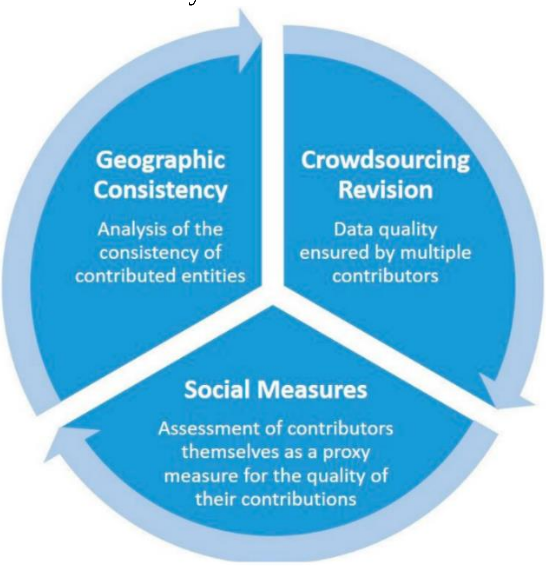


Figure 77. Three domains of a VGI Quality Framework (Source: Goodchild and Li, 2012).

Navratil & Frank (2013), examined how these three approaches may be adopted in land administration to assure that crowdsourced geospatial data may provide a reliable source. As crowdsourced and VGI data are user-generated, they are strongly affected by contributors' personal knowledge, interests and willingness. In case of land administration, where for example property boundaries are of main interest, VGI data may be a reliable source only if boundaries are obvious by direct observation. However, the majority of such cadastral information is only known by a few of people, mainly owners, or by professional surveyors after the necessary measurements. Thus, based on this fact, crowdsourced cadastral data may be reliable if the contributors are mainly owners or trained citizens in cooperation with owners.

4.3.3 Accuracy of Crowdsourced data

The volunteer-crowd collected data may not meet always high levels of accuracy as the data is produced by heterogeneous contributors, utilizing different technologies and tools, serving heterogeneous purposes and a lack of gatekeepers (Senaratne et al., 2017). During the past decade, several studies are focused on the positional accuracy of crowdsourced data. Haklay (2010), investigate the accuracy and completeness of OSM's linear objects representing motorways by comparing them with an authoritative map. After a geometric assessment concluded that the OSM data is quite accurate with an average positional discrepancy of about 6 meters. Beyond the positional accuracy of linear features, the accuracy of OSM's Points of Interest (POIs) (e.g., hospitals, schools etc.) were also examined. Hristova et al. (2012) evaluate OSM positional accuracy using Euclidian distance from reference point objects, concluding that the average discrepancies were about 6.65 m. A similar investigation was conducted by Al-Bakri & Fairbairn (2010) by comparing OSM point data to reference - ground truth - field survey dataset. In order to estimate the positional accuracy, the RMSE (Root Mean Square Error) measure, was utilized. The comparison showed that the OSM point data do not match with the reference dataset, differentiating more than 10 m.

In the following years OSM positional accuracy continued to concern the scientific community, with researches proving that accuracy measures are improving mainly in urban areas, while in rural and undeveloped areas inferior results occurred (Cetl et al., 2019). Haklay et al. (2010) investigated whether the positional accuracy of intersection features may be improved through increasing the number of contributors. Authors have concluded that the overall aggregated location accuracy did improve, although no effort was made to study whether previous versions can contribute the overall positional accuracy. Beside these findings, no one of the aforementioned researches have explored an alternative way of improving crowdsourced data quality and accuracy. In 2016, Zhao et al. (2016) introduced a spatiotemporal VGI model which considers contributor reputation and object trustworthiness. By collecting information regarding contributor's experience and trust, the achieved accuracy of mapping may be further improved (Foody et al., 2015).

Besides these promising steps that crowdsourcing has implemented, there are several researchers who expressed their doubts regarding the potential use of crowdsourcing and VGI data in governmental projects (Helbich et al., 2010). One of the first attempts, trying to highlight the need for an alternative crowdsourced approach in land administration, was proposed by Laarakker & de Vries (2011). The main objective was to indicate the imperative need of an open and flexible cadastral system. Through this attempt which was named OpenCadastralMap, the author tried to categorize the main concerns regarding the implementation of such program. They conclude into two categories referring to the technical and the socio-organizational aspects. The technical include the quality control of OSM, OpenCadastreMap and the utilized technology. The socio-organizational referred to the understanding of the project importance, the role of the government, the legality control and the economic factor. Since then, the investigations regarding this matter have attracted the growing interest of the research community. Navratil & Frank (2013) and De Vries et al. (2014) followed this path by investigating the term Neo-cadastres, trying to explore the involvement of VGI within the traditional cadastral methods.

During the following years, research in the field of land administration is intensified, with the development of alternative methodologies and modern technical frameworks, leading to results of much higher accuracy than expected based on older researches. However, the basic question that needs to be answered in order to evaluate the achieved accuracy is the following: *Which is the required quality of the collected data according to the purpose of the surveys (fit-for-purpose)*? Fit-for-purpose means that the land administration systems – and especially the underlying spatial framework of large scale mapping – should be designed for the purpose of improving the management of current land issues within a specific country or region – rather than simply following more advanced technical standards regardless the cost and time delays for the completion of the project (Enemark et al., 2014). So it seems that a fast, reliable but not highly accurate solution can be a starting point for the initial collection of cadastral information.

As described in detail in the Section 4.3.1 the utilization of modern technological achievements, large scale orthophotos and training sessions, the relative accuracy of the collected crowdsourced data may be increased. In Apostolopoulos et al. (2018) the maximum positioning error in the determination of boundary nodes in urban areas was approximately 1 m, while the overall recording procedure is performed with a relative accuracy of about 0.5 m. Also, in the sub-urban area the average deviation was about of 0.6m and the maximum deviation was approximately 1.7 m. The difference in accuracy between the urban and sub-urban areas are due to the dense network of antennas in urban areas which enable a more accurate estimation of the mobile device's position (Mourafetis et al., 2015). Subsequently, Molendijk et al. (2018) support that a sub-meter accuracy for the collected points may be provided, due to the utilized configuration including the Trimble R2GPS device. Observing the results of subsequent studies appears that the achieved accuracy is improved further. Also, in Potsiou et al. (2020) the achieved positional accuracy was about 0.4 m for urban and 1.0 m for rural areas. These results seem to satisfy the cadastral requirements of both countries, enhancing the potential of exploiting crowdsourced data in the initial phases of the cadastral formal procedures.

With the advent of social media, crowdsourced technology, GPS and imagery available on the internet, there is an opportunity for establishing land administration capacity even in places that previously could not afford such systems, and to provide qualitative, reliable and transparent land administration services in places where corruption and inefficiency is endemic (Adlington, 2011).

4.3.4 Application Usability Inspection

Usability provides one of the most important parameters in designing products, as it affects the users' reaction concerning the product. In ISO 9241-11 (1998) a definition about usability is presented, as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use". As specified in ISO/IEC 25010 (2011), the quality of a product may be defined by 8 parameters "functional suitability, reliability, performance efficiency, usability, security, compatibility, maintainability and portability". With regard to usability, the necessary characteristics that may represent a usable application interface are the recognisability, learnability, operability, user error protection, user interface aesthetics and accessibility (ISO/IEC 25010, 2011).

Usability presents a qualitative way to assess how easy the user may interact with applications interface. Nielsen (2012) defines usability as a combination of five quality components, as follows:

- Learnability: how easy it is for users to complete some basic tasks during their first interaction with the applications' interface.
- Efficiency: the necessary time for users to accomplish a task once they have learned how the system works.
- Memorability: how easily can users re-interact with the systems' interface after a period of not using it.
- Errors: the errors that the users make when performing tasks and how easily they can recover from them.
- Satisfaction: how pleasant it was for the user to use the system.

Usability evaluation is important in order to improve applications interfaces, aiming to produce more qualitative products and therefore qualitative data useful for several applications.

4.4 Conclusions

In the realm of digital revolution, VGI and crowdsourcing claims a key position as a tool for collecting and sharing geospatial information through the internet. The rapid expansion of the smartphones with integrated sensors, cameras and internet access facilitates this process, promoting the further development of this field. Initially, VGI communities were focused on the 2D domain, but gradually various efforts were made both in adding information regarding the 3rd dimension of the already collected data, as well as for directly create and disseminate 3D geospatial content. The concept of 3D modeling or 3D reconstruction of buildings is often associated with the implementation of complex processes and the utilization of professional software exclusively by experts. However, today a variety of freely available or open-sourced solutions have been developed, allowing the generation of 3D models by people without special photogrammetric skills. Thus, it is enough for the individual to be interested in contributing in order to easily create a 3D building model through the use of parametric shape libraries or freely available modelling software.

The introduction of crowdsourcing in land administration caused a variety of objections and disagreements mainly in terms of data quality and the arbitrary consideration of abolishing the role of the surveyors. However, one of the fundamental questions that need to be addressed when dealing with crowdsourced data is: "*Does the achieved data quality satisfy the purpose of the surveys*?" As evidenced by the current research a large percentage of the developed and developing land is not officially registered, leaving the property rights at risk. In addition, it has been proven that traditional cadastral surveys require time and funds, which may gradually increase, complicating or even prohibiting the completion of cadastral surveys. This may lead to an increment in rights holders' uncertainty regarding their rights as well as the time and costs involved in land and property transactions and mortgages, blocking the real estate market and inhibiting poverty reduction. Especially in developing countries the perpetuation of this treaty can disrupt the peace agreements and maintain the poverty conditions. Thus, the preservation of property rights seems imperative even if it is not implemented with the high precision specifications, as settled by the current 2D land registers. A fast, reliable but not highly accurate solution can be a starting point for the initial collection of cadastral information.

During the past few years, crowdsourcing has claimed a critical role as a reliable methodology with huge potential regarding the realization of 2D cadastral registration in both an affordable and a timely manner. The adoption of new technology in cadastres is supported by the experts, including modern technological achievements such as mobile devices. Despite the initial doubts, the application of crowdsourcing techniques in the cadastral surveys can achieve remarkable positional accuracy. Using the GPS sensor of the mobile device or an external GPS antenna, a sub-meter and meter accuracy may be achieved in urban and suburban, rural areas respectively. It is worth mentioning that the achieved accuracy may meet the specifications of several countries, enhancing their potential in the initial phases of cadastral formal procedures. However, their improvement at a later stage of the cadastral procedures is not ruled out, on the contrary, it is desirable.

Besides positional accuracy, there are also other factors that distinguish and ensure the quality of the crowdsourced data, concerning the completeness, logical consistency, thematic accuracy, temporal quality and usability. Satisfying all of these conditions requires the development of a well-structured "fit-for-purpose" approach always under the supervision of a professional surveyor. The control of the crowdsourced data by professional surveyors is necessary to identify weaknesses, provide solutions and lead the overall procedure. In addition, the success of this attempt is directly affected by the characteristics of the data capturing tool and the approaches followed to recruit and encourage citizens to join such crowdsourced project. Finding the balance in which citizens wish to collect and contribute data through a relatively simple procedure in a way that quality of the data does not deteriorate. By relying on international standards, such as LADM, commonly accepted application development specifications and providing the appropriate incentives for participants, the development of a promising solution for the implementation of both cadastral surveys is feasible.

It is worth noting that in some countries, such as Greece, the cadastral surveys are already participatory while the use of a web and a mobile application for the declaration of property rights from the right holders, is integrated into the official procedure of the 2D Hellenic Cadastre. Although crowdsourcing has shown great potential in supporting the 2D cadastral surveys, its introduction in 3D cadastral surveys posed additional challenges and thus still need further investigation. By adopting the lessons learned from the 2D domain, it is possible to develop an equally efficient approach that supports the 3D domain. Especially in cases of complex and multidimensional property rights that pervade the modern world, the immediate determination of properties boundaries and their legal extent, which is best known to owners, is particularly important. To date, the studies referring to the 3D aspect of the cadastral objects do not lead to the development of 3D property models. However, through exploiting the capabilities of the modern ICT tools and 3D reconstruction methods, the development of the 3D property models is feasible. As demonstrated in this chapter, utilizing parametric reconstruction methods seems to be the best choice for managing the crowdsourced data and proceed with 3D modelling. Thus, appear that the proper management and utilization of the 3D information can lay the foundations for the development of 3D cadastres worldwide.

Chapter 5

Compilation of 3D crowdsourced Cadastral Surveys

As modern cities have a multi-dimensional growth, safeguarding of tenure requires the 3-Dimensional (3D) identification of property RRRs, through the establishment of 3D cadastres. As has already been proven by the global efforts regarding the development of 2D cadastres, the implementation of 2D and therefore of 3D cadastres has also high demands on time, finances, equipment and human resources. These requirements make it difficult or even prohibit the compilation of the property registration, increasing the uncertainty of ownership rights and blocking the real estate market and rights holders, in a stagnant state. As a result, many countries do not have a complete 2D land registry until today.

The immidiate development of a functional 3D cadastral system is of a great importance for both the developed and the developing world, as it ensures ownership rights, reduces risks, time and costs in urban property markets, and enables poverty reduction. This perception is contended by several actors such as UN-Habitat and the International Federation of Surveyors (FIG) (Lemmen et al., 2015). A fit-for-purpose 3D crowdsourced cadastral surveying approach seems to be the most appropriate solution, in order to meet the 2030 UN Agenda SDGs and ensure that both developed and developing countries may develop functional land administration systems fast and reliable with affordable costs, utilizing international standards (Enemark et al., 2014). Low-cost equipment, crowdsourcing techniques, machine learning techniques, automated procedures, mobile services (m-services), web services and open-source software (OSS) as well as standardized international data models, sign a new era for the cadastral data acquisition, recording, exchange and dissemination procedures, reducing the cost and the time of the required cadastral surveying (Cetl et al., 2019).

In order to overcome the existing difficulties and establish 3D cadastres in a short time frame, the minimization of the financial and human resources, is required. Undoubtedly, one of the costliest phases of the implementation of 3D cadastres, is the initial 3D data capture. Recent research has proved that low-cost sensors and cameras often available in smartphones, enable the 3D geospatial data acquisition by non-professionals, such as citizens. Thus, each citizen may be defined as potential neo-photogrammetrist (Leberl, 2010), who can collect 3D data and develop models using modern 3D reconstruction algorithms and tools. This allows, for example, the reconstruction of 3D objects based on 2D images taken by low-cost sensors (Uden & Zipf, 2013). This may complement the data collection procedures of the property rights information so as the property's geometric information. Moreover, 3D data collected in other areas, such as BIM, IFC CityGML files, IndoorGML, InfraGML and LandXMLetc., can also be used for the creation of a 3D cadastral database (Dimopoulou et al., 2016).

While the activities of the various VGI and Crowdsourcing communities has not substantially changed the way bodies such as National Mapping Agencies (NMAs) produce data, a change in the future is anticipated (Foody et al., 2015). In this Section a methodology for the future data collection, management and 3D modelling of cadastral objects is developed and presented. This effort aims to provide a more generalized procedure adjustable to the available cartographic infrastructure and financial situation of each country, including even regions that still lack a 2D cadastral data registration. First, the leading principles followed for the development of the crowdsourced methodology, are reported. Next, the legitimate means for data acquisition and the potential types of geospatial infrastructure, aiming to support the crowdsourced methodology, are presented. Subsequently, the main workflow of the crowdsourced methodology for the initial implementation of 3D cadastral surveys, is described and illustrated; while a Greek paradigm trying to adopt the crowdsourced workflow in the Greek reality, is followed. Finally, the main conclusions regarding the perspectives of the developed methodological approach for the initial implementation of 3D cadastral surveys, are presented.

5.1 Leading Principles

The development of the current methodological approach relied on a series of research findings, lessons and trends in order to provide a viable and efficient model for the implementation of 3D crowdsourced cadastral surveys. Each one of the adopted components has a crucial role in the design of both the methodology and the technical tools for its implementation. The leading principles are depicted in Figure 78.

- *Briefing, Motivation and Training*. One of the most important parts – if not the most important part – for the success of a crowdsourcing project is citizens' gathering and briefing about the main objectives of the project and the motivations that will be provided to the participants. The local community should be informed about the whole procedure and get notified about its benefits. Thus, incentives will be provided to the participants creating greater interest for their accelerated participation. Furthermore, through proper training, the reliability of the procedure is increased while the implementation time is reduced, reaching quickly the desired result.
- *IT Tools and Software*. The selection of the appropriate data capturing tool is an important parameter affecting both the accuracy and reliability of the collected data, as well as the recruitment of the participants. In the majority of crowdsourced projects, the utilization of mobile devices has a prominent role, as they are an integral part of citizen's everyday life. The utilization of a mobile-based or web-based application enables the acquisition of data remotely, facilitating users to contribute from distance. The development of a 'user-friendly' mobile application following the internationally accepted ISO/IEC 25010 (2011), may function positively in the effort of recruiting right holders in the crowdsourced procedure.
- *Active Collaboration - Proper Assistance*. Collaboration between citizens and professionals as well as with the current National Cadastral Mapping Agency (NCMA) is needed. The roles and duties between all the involved parties have to be well-defined from the beginning of the procedure. The enactment of proper assistance in each part of the process by professionals or specially trained individuals, offers better coordination leading to compact results.
- *Innovative techniques*. Besides the crowdsourced aspect of the developed methodology, there are several requirements that need to be met in a land administration project. The most important parameters refer to the quality, reliability and management of the collected data, even in cases of week geospatial information availability. In particular, the acquisition of 3D geometric data and their further manipulation for the generation of 3D models, retaining low the cost and time of the procedure, require the development of innovative techniques exploiting the recent technological developments.

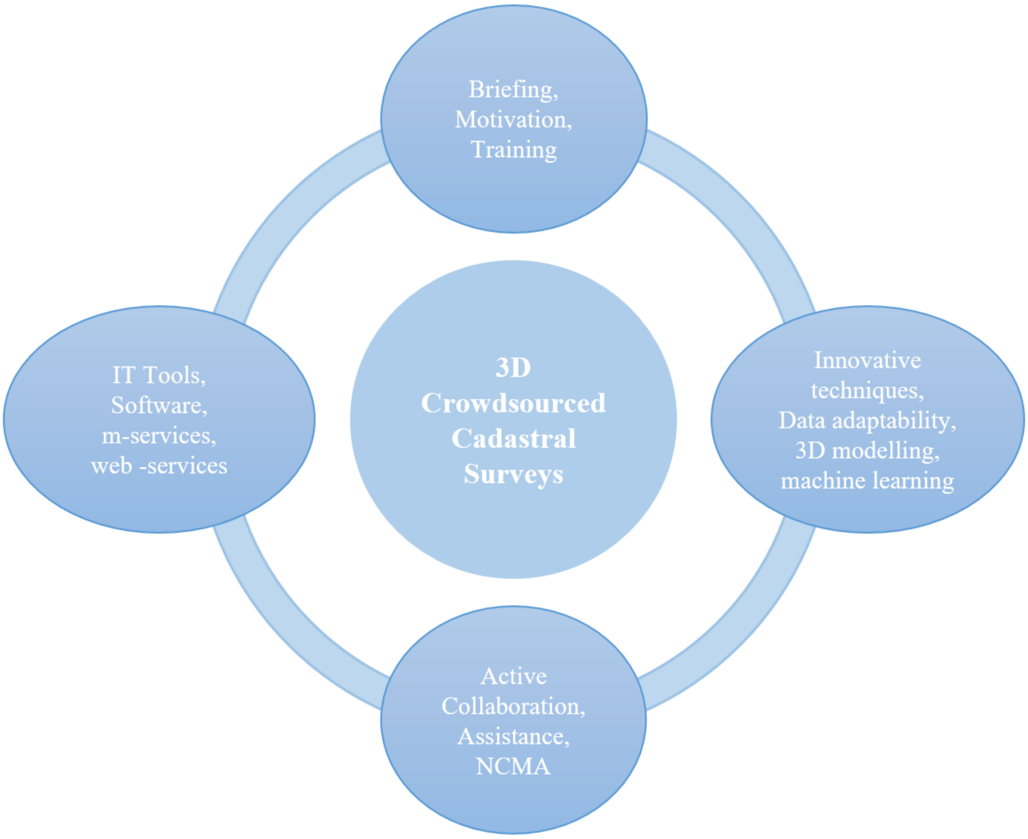


Figure 78. Main principles of the 3D Crowdsourced Approach for the implementation of 3D Cadastral surveys.

5.2 Data Capturing tool

The selection of the most appropriate tool for the implementation of cadastral surveys is something that strongly influence the outcome of both the traditional and modern cadastral procedures. In land administration crowdsourced projects, the utilization of a mobile applications with GIS functionalities, is more expedient as allows the rights holders to move throughout the property using – when needed – the GPS sensor of the mobile device and collect directly the necessary information and/or measurements. The selection of mobile applications in cooperation with wireless services are inclusive and preferable as not everyone has access to a cable internet. Through selecting a mobile application, the implementation range of the crowdsourced approach is widened enabling both the developed and developing countries to have access to a trusted land registry, ensuring their rights.

In the developed crowdsourced framework, a mobile cadastral application is selected as the main mean utilized for the acquisition of basic 3D geometric and descriptive cadastral information. The main purpose of the mobile application is to provide an easy solution to the right holders in order to automatically produce and visualize 3D semantically enriched property unit models, located above or below the ground surface, by inserting the appropriate geometric and descriptive information through the mobile application as well as all the supporting legal documents and additional evidence about the rights and rights holders.

Certainly, the use of a mobile application does not constitute the only effective solution capable of supporting the 3D cadastral procedure. A web application or a combined use of a web and a mobile application consist powerful alternatives tools for such a crowdsourced approach. For example, a mobile application may be utilized for the acquisition of the geometric

3D data while a web application may be utilized for the submission of the legal documents and additional evidence about the rights and rights holders. Therefore, the option(s) of the application(s) for the proposed crowdsourcing framework for 3D cadastral surveys varies and may be adjusted according to the current needs and the available infrastructure of each country.

Besides that, both mobile and web applications are assessed by the author of this dissertation, the utilization of a mobile application as the main data capturing is predominated. Examples of a cadastral mobile and web applications capable of 3D data acquisition, 3D parametric modelling and/or visualization of 3D property models, are developed and presented in Section 4.1.

5.3 Geospatial Infrastructure

One of the key parameters for the implementation of a 3D land registration system, is the type and the quality of the available geospatial infrastructure, that may be used for the declaration of the 3D RRRs. As the available geospatial infrastructure differs from country to country, the selection of the appropriate basemap is crucial and should be based on the options available for each country.

However, the introduction of the third dimension in land registration systems, broadens the range of the potential recording background beyond the traditional cartographic, leaving room for new innovations to be explored. This means that alternative solutions should be explored for both the cases of poor geospatial infrastructure, so as for the cases of high-quality data availability. By exploring how the 3D property rights can be defined and represented in each of these cases, the development of an adaptive crowdsourced methodology for the initial implementation of 3D cadastres is feasible. An overview of the alternatives data sources is illustrated in Figure 79 and it is described in detail below.

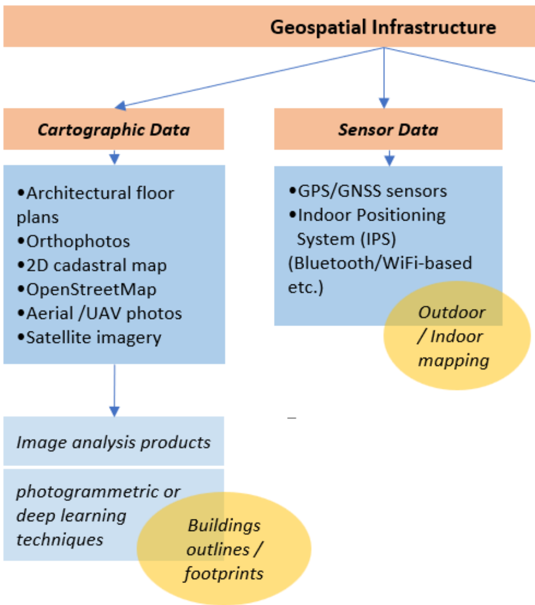


Figure 79. Overview of the alternatives data sources for the implementation of 2D/3D crowdsourced cadastral surveys.

5.3.1 Cartographic Data

In countries with well-functioning 2D cadastres, a 2D cadastral map overlaid on a large scale orthophoto can be used as registration basemap. To enhance the reliability and accuracy of the 3D crowdsourced cadastral surveys, architectural floor plans may then be matched with the digitized building footprints. In this case, the cadastral information can be classified as Accurate, Assured and Authoritative (AAA) (Williamson et al., 2012; Gulliver, 2015) and the geometric accuracy that meets specifications can be ensured (Mourafetis et al., 2015). In the absence of architectural plans or/and orthophotos of high accuracy, horizontal plans of each floor of the building made by the rights holders showing the individual property units and an orthophoto of less accuracy, or an aerial photo taken from various platforms (e.g., UAVs), or even the OpenStreetMap (OSM, 2022), may be used instead, thus reducing the geometric accuracy significantly. This process together with the creation of a digital 2D cadastral map, may be followed in cases of countries with incomplete or without a 2D land registry. In the latter cases the land parcel boundaries and the building footprints should be visible on the available basemap. This is usually the case in urban areas where boundaries are fixed on the ground and this obviously increases the accuracy of digitization. In any other case, more sophisticated techniques, should be followed.

5.3.1.1 Image-based Analysis Techniques

The information provided through the 2D cadastral maps and/or the architectural plans of buildings is of a great importance for the compilation of 3D cadastral surveys, as they delimit the building's boundaries and/or the individual properties/building units, facilitating the right holders to locate and digitize their properties accurately on the available basemap. In their absence, the right holders may create a 2D cadastral map depicting these boundaries, but the achieved accuracy will be relatively low, as it will depend solely on the judgment of each right holder. However, recent research trends have shown that aerial remote sensing data, such as aerial photos, UAV photos, orthophotos, satellite images etc., may be exploited by modern photogrammetric or deep learning techniques, providing valuable metric and descriptive information regarding the location and the boundaries or footprints of the depicted buildings. As it is described in Chapter 3, buildings' outlines may be detected and extracted from the available aerial imagery, providing important geospatial information about the buildings. In the context of this doctoral dissertation, two separate methodologies were developed aiming to detect and extract the buildings' roof tops surfaces and vectorized buildings' outlines, respectively. As it had been proven, these methods do not have high demands in terms of finances and time while they lead to reliable and accurate enough results, comparatively with the purpose of the developed crowdsourced framework. Such geometric information consists a reliable data source that may be also utilized as an alternative basemap for 3D registration of RRRs', strengthening the developed crowdsourced framework. The right holders may identify their properties more easily and utilize the depicted buildings' boundaries as reference, in order to locate and digitize their own property/building unit.

5.3.2 Sensor Data

5.3.2.1 GPS-assisted

If the land parcel's and building's footprint boundaries are not visible on the available basemap, there are several options to proceed with their identification, such as (a) by using the smartphone's GPS sensor with an accuracy of a few meters, or (b) by using external support GNSS (Global Navigation Satellite System) tools and resources, achieving high positioning accuracy. As shown in Mourafetis et al. (2015), the achieved accuracies using the GPS sensor of mobile phones are high in urban areas, due to the dense network of antennas, while minor corrections can also be achieved by moving the cursor on screen and locate it to the correct position on the available basemap.

Utilizing the Bluetooth capability of smart devices, different mobile GNSS receivers may be connected with smartphone's positioning applications, providing reliable and accurate results. For example, Esri's Collector Application may be connected with Trimble R2GPS GNSS receiver device, providing sub-meter accuracy for the observed points (Molendijk et al., 2018; Cetl et al., 2019; Potsiou et al., 2020), or with EOS Arrow Gold RTK GNSS receiver device (EOS_RTK_GNSS, 2020), providing even centimeter accuracy for the observed points. These configurations may provide accurate and reliable results in outdoors spaces for field work.

However, this is not the case for the indoor environment, where the positioning problem is more challenging as the GPS/GNSS signal is weak in the interior of buildings and therefore indoor positioning relies typically on local infrastructure/measurements and other type of support. Thus, in the absence of accurate floor plans to be used as basemaps, the digitization of the property unit boundaries is based on methods trying to replace the operation of GPS at indoor environments.

5.3.2.2 IPS-based

Capturing the geometry of building's property units/condominiums in cases where the architectural floor plans are not available, is very challenging. This is amplified when the identification of the individual properties units is requested to be implemented by the right holders/citizens utilizing a basemap which at best can clearly depict the boundaries of the land parcel and the building's footprint, without providing any further information regarding its' interior configuration. During the research of this doctoral dissertation, it emerged that the development of an Indoor Positioning System (IPS), with structure similar to the one described in Section, can work beneficially in solving this problem.

An IPS based on low-cost Bluetooth technology can work in collaboration with a 3D cadastral mapping mobile application, providing the necessary location information, in order to support the 3D crowdsourced cadastral surveys. The main idea of the designed IPS solution is to gradually construct the plan of indoor cadastral spaces/property boundaries, through tracking the mobile device's/user's trajectory. Through the cadastral mobile application and the smartphone's Bluetooth wireless sensor, right holders may 'visit' their property and delineate the boundaries of their indoor cadastral spaces on the basemap, utilizing the established IPS. By processing the received IPS signals through a machine learning algorithm the generation of horizontal spatial information, regarding the position of the mobile device in the indoor environment may be provided and visualized through the cadastral mobile application (Figure 80). Thus, right holders may gradually construct the boundaries of their property unit (indoor cadastral space), by moving towards the physical boundaries of their property and digitize them by selecting their corresponding position on the basemap.

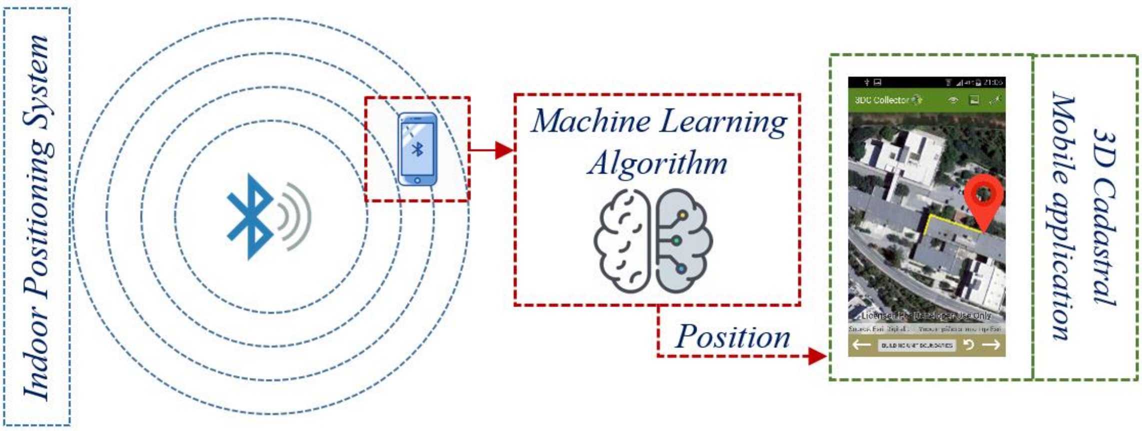


Figure 80. 3D cadastral indoor mapping – Framework overview.

5.3.3 3D Data Models

Besides the 2D geospatial options, the utilization of already existing 3D data models (BIM, CityGMLetc.), may also facilitate the registration of buildings as 3D spatial units. Furthermore, other available 3D data sources (dense point clouds, etc.) in cooperation with modern 3D reconstruction techniques and algorithms, may provide an accurate 3D registration basemap able to guide the 3D cadastral surveys.

5.3.3.1 BIM data

BIM is considered as the most comprehensive and intelligent 3D digital approach able to manage buildings with composite structures, and enable communication between stakeholders with different backgrounds (Atazadeh et al., 2019). The world of smart cities needs proprietary BIMs, as a clarifying tool, providing a clearer picture with relation to property RRRs. BIM and 3D property are two seemingly different domains but they can interact and get benefits from each other.

While BIM may be used to provide the geometry of the complex physical buildings' spaces for 3D Cadastre (rooms, corridors, walls and floors), the legal space needs to be related with only one space describing the ownership boundary of a single property. In this legal bounded area, the RRRs corresponding to the property, are assigned. Through binding a number of physical spaces (rooms) or parts of physical spaces (to the middle of the wall space), the legal spaces of ownership rights, may be defined. Thus, a 3D spatial representation derived from a BIM may present an apartment which spread across multiple rooms but belonging to one owner. This could provide a better understanding regarding properties boundaries, ensuing clarity to legal issues and avoiding improper behaviors and disputes between the stakeholders (Oldfield et al., 2016; Shin et al., 2020). The representation of legal spaces can be supported from open BIM exchange models.

The commercial products are increasingly supporting open BIM standards, facilitating the broad utilization and exchange of BIMs. The standard used in this particular investigation is the Industry Foundation Class standard (IFC), which constitutes one of the most widely used standards. The IFC is a set of object definitions and exchange formats that promote interoperability between different platforms and define buildings elements, presenting the spatial relationship among them (Borrmann, 2018; BuildingSmart, 2022). Among 3D data models, IFC provides the potential capabilities for modelling legal and physical dimensions of urban properties (Barzegar et al., 2021). With IfcSpace entity, the representation of volumetric spaces inside a building is feasible. Thus, the interior structural elements can be included into this entity, forming the legal spaces of the cadastral objects, where the RRRs will be assigned.

5.4 Workflow

The developed procedure focuses on the most expensive and time-consuming phase of the implementation process, which is the 3D cadastral data acquisition including the semantic information of the ownership status and other rights, as well as the 3D modelling and the visual representations of the property units. As the legislation and the cadastral surveying procedure differ from country to country, this approach aims to introduce a flexible framework in order to save time and funds, and to provide a fast and inclusive solution for the initial implementation of a 3D property registration, even in areas that still lack a 2D cadastral data registration. The main components of the crowdsourced framework are the rights holders' active participation, the exploitation of modern IT tools, m-services, web-services and the development of an innovative 3D reconstruction algorithm for automatic 3D modelling and/or the proper visualization of the main entities of a 3D cadastre, which are the individual property units. The workflow of the developed methodology is shown in Figure 81.

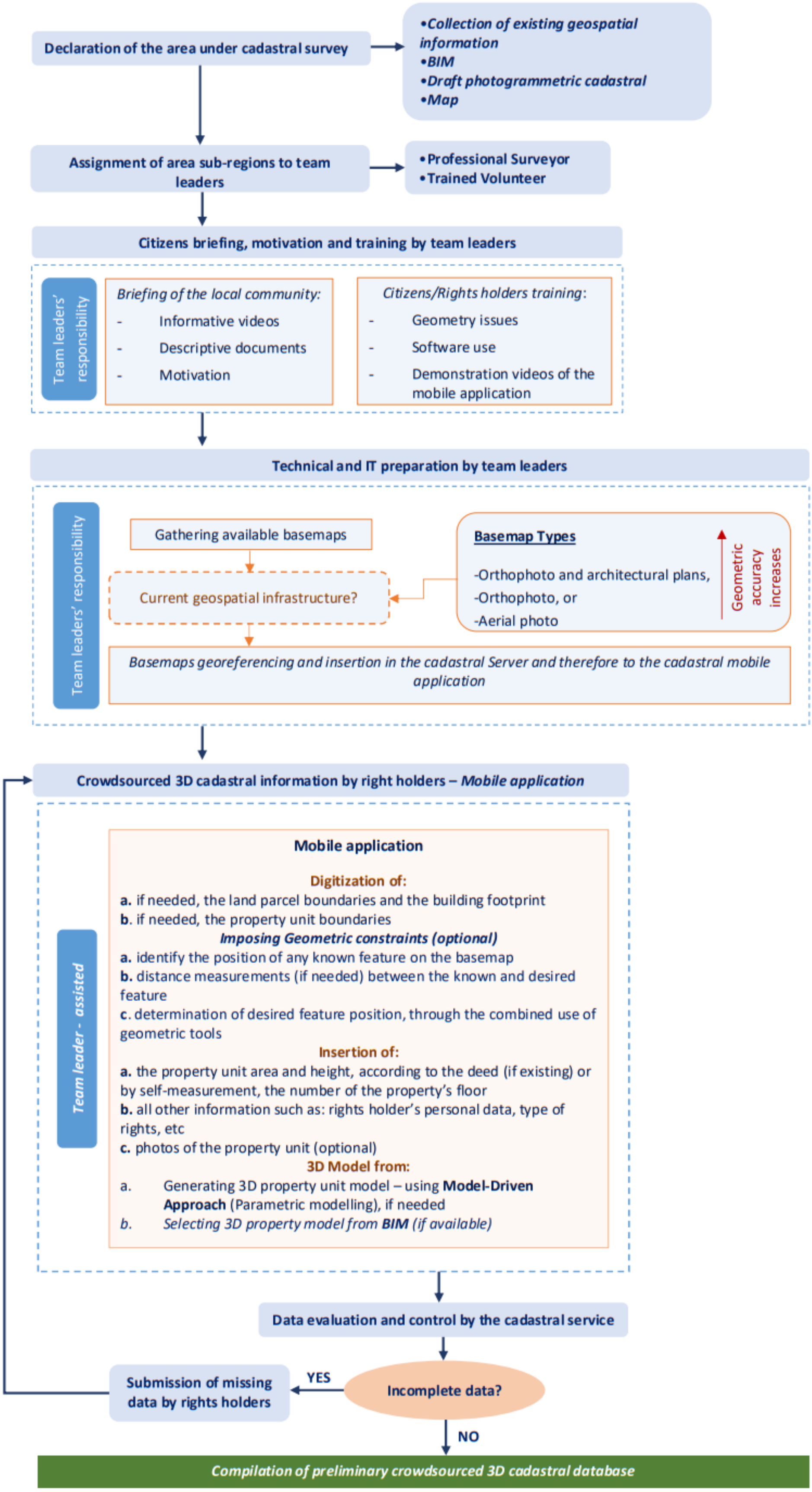


Figure 81. *Proposed crowdsourcing methodology for 3D cadastral surveys up to the stage of the compilation of the preliminary 3D cadastral maps and data.*

The proposed crowdsourced procedure starts with the declaration of a specific area under cadastral survey by the municipality, and the preparation of a basemap to be used for 3D cadastral data collection. The NCMA should provide a recent basemap as well as any existing geospatial information that may have created cadastral information in the declared area. During this phase, it will be helpful if a professional collects all existing cadastral information and integrates it with the available basemap. In some cases, a professional may also try to predict the parcel structure according to what boundaries are visible. Furthermore, 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.

In the second phase, the area under cadastral survey is divided into sub-regions and each of them is assigned to a professional surveyor or a trained volunteer with the role of the team leader, who heads and assists the citizen/right holders to get through any difficulty regarding the overall cadastral procedure. Through this real-time assistance, the duration of the surveys and the gross errors are being reduced while the reliability of the collected data is being increased.

In the third phase, team leaders are briefing citizens through the cadastral process, introducing the expected benefits from this crowdsourced project to them (Figure 82). Simultaneously, team leaders are responsible for citizens/right holders training mainly in geometry and legal matters and on the usage of the cadastral application. Apart from the task of the team leaders, informative videos and detailed explanatory documents should also be provided by the NCMA. In order to motivate and recruit citizens to this project, NCMA may provide a motivation reward to the participants, such as a discount rate on taxes or registration fees or may utilize gamification techniques (Apostolopoulos et al., 2018). Such actions strengthen the will for citizens' participation in social processes with a positive impact on its outcome.

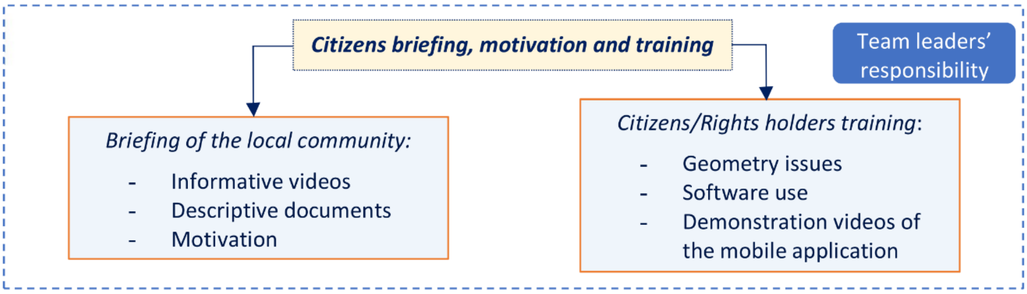


Figure 82. Third phase of the proposed methodology.

Subsequently, in the fourth phase the team leaders should be responsible to gather any available plans to be used as basemaps, such as scanned architectural plans, BIMs – if existed, and to care for the georeferencing of such raster data or models –if needed, and the insertion of these as registration basemap into the cadastral server and therefore to the cadastral application. This process consists the fourth phase of the proposed methodology and is shown in Figure 83.

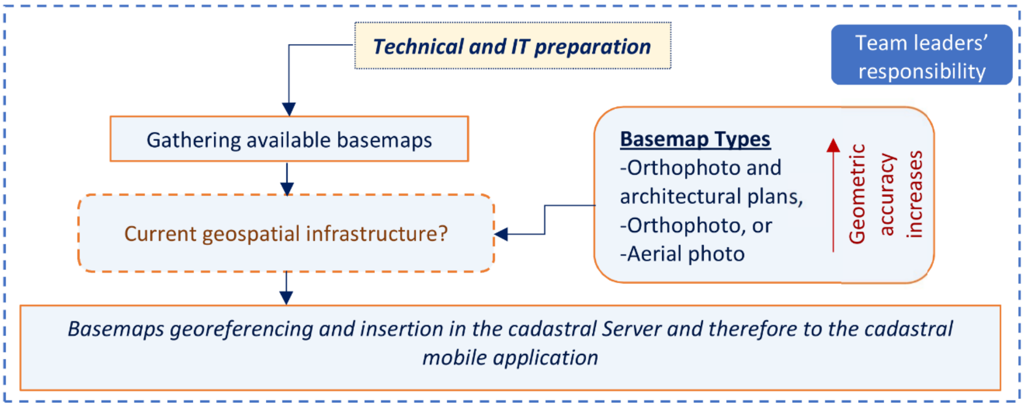


Figure 83. Fourth phase of the proposed methodology.

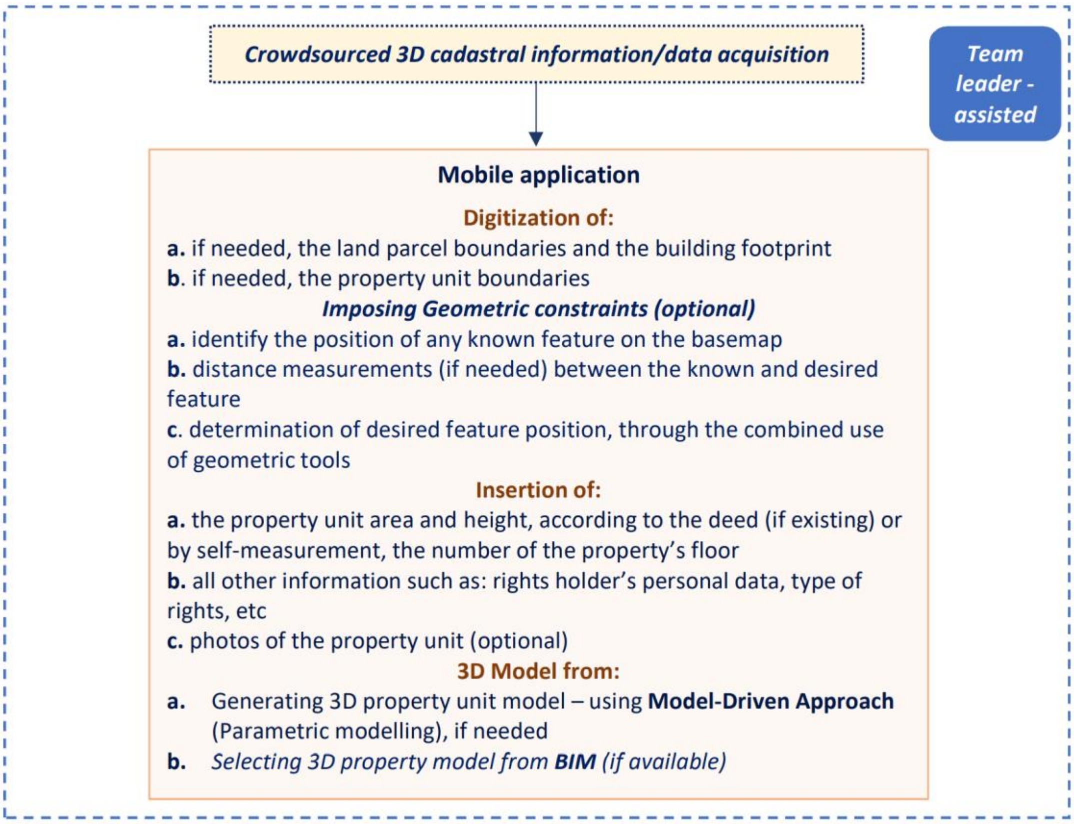


Figure 84. Fourth phase of the proposed methodology.

In the fifth phase, the 2D/3D cadastral surveys are performed by the citizens/right holders, through the cadastral application (Figure 84). In case of "parcel-based" land administration systems, the property RRRs refer to the land parcel and to the building, and thus both instances should be identified and collected. In established and well-functioning 2D cadastres, the land parcel unit and the building footprint are already registered and included in an updated cadastral map, forming a qualitative basemap on which 3D cadastral surveys may be based. On the contrary, in areas with incomplete 2D cadastres, a digital 2D cadastral map update must be recorded first, in order to proceed with 3D registration. In the latter case, the land parcel boundaries as well as the building footprint may be identified on the available basemap, whose type depends directly on the budget available. Thus, depending on the progress status of the current cadastral system, the right holders will be asked to submit the boundaries of the parcel and the individual property units (condominium) for which they have rights – when needed, together with photos or files of all available legal documents proving their rights. It is noted that the utilization of a crowdsourced cadastral survey approach, in order to initially collect such 2D data and proceed with the 3D registration, may lead to an effective solution both in developed and developing countries. As has been already proven in earlier publications, the rights holders can easily identify and digitize the required property boundaries on the available basemap, illustrated on their mobile phones' screen (or laptop, or tablet) (Mourafetis et al., 2015; Gkeli et al., 2016; Jones et al., 2017; Apostolopoulos et al., 2018; Molendijk et al., 2018; Cetl et al., 2019; Potsiou et al., 2020; Mourafetis & Potsiou, 2020).

Certainly, the NMCA should provide the rights holders/citizens with a cadastral application capable of supporting 3D cadastral surveys (Figure 84). Through the cadastral application, the identification of the property boundaries on the available basemap may be done by the rights holders and/with the support of team leaders or other non-professional assistants (this can also be an e-training course provided by the NMCA). Simultaneously, the holders of rights may submit information about the property: unit height, the area according to the deed (if existing) or by self-measurement; the number of the floor on which the property unit is located; other information, such as rights holders' personal data and type of rights; and verification images (photos) of the property unit (optional). The submission of the legal documents and additional evidence about the rights and rights holders may be done directly through the cadastral application from the rights holders, by attaching them either as scanned documents or as photos. All this declared information is fundamental to the automatic 3D modelling of each property through the cadastral application – when needed – and, finally, generation of a reliable 3D cadastral database. With the determination of each property unit boundaries, especially in cases of multi-story buildings where multiple properties exist, information about the building interiors is also revealed, leading to a real 3D representation of the buildings and not just a 2.5D representation.

By the completion of this phase, the NCMA will have a draft 3D building and property unit database conducted by the rights holders. The evaluation and control of this database 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 (Figure 81). Following the examination of objections and the correction of data, property titles may be provided -if needed- and property registration is compiled.

5.5 A Greek Paradigm

In this Section, an attempt to adapt the crowdsourced workflow in the Greek reality, is made. At First, an investigation regarding the structure of the Greek Land Registry and the current Greek legislation is conducted, while then the Greek workflow is formed and presented.

Greece is an EU country that does not have a complete 2D Cadastre for all of its territory while at the same time consists a great example of overlapping and complex proprietary RRRs. The compilation of a functional cadastral system, able to manage both the 2D and 3D aspect of the cadastral object is considered to be an urgent issue not only because Cadastre is an important governance tool but also because it consists a tool for safeguarding the land tenure and ensuring access to credit, assisting the economic recovery of Greeks.

5.5.1 Hellenic Cadastre

The Hellenic Cadastre (HC) project started in 1995 with the Law 2308/1995 (Government Gazette A΄, 114/15-06-1995). 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 consist a 'land parcel-centric' digital Geographic Information System (GIS) that is aimed to cover the whole Greek jurisdiction and address any lack of spatial data. 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 National Mapping Agency (NCMA S.A.) is responsible for both the collection of all necessary spatial information regarding land parcels and the registration of all the legal rights concerning them as attribute documentation.

5.5.1.1 Main Stages of the Hellenic Cadastre Survey

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) (Figure 85). The cadastral surveys are conducted by private cadastral companies (contractors) which are selected by the NCMA. Before the field processes begin, 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-existed 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.

In the next phase, the declarations are gathered and processed by the contractor, while then they merged with other collected data provided by the public authorities. In cases where discrepancies in the collected data are occurred, the contractors must proceed with the implementation of field cadastral surveys in the study area, in order to examine and correct these data. Also, if needed, additional data may be supplied by the right holders. Once the information processing phase is completed, the contractors are responsible to inform the right holders about the results of this procedure, through the pre-publishing process. Next, the preliminary cadastral data is published at the NCMA's offices for a two-month period while excerpts of the cadastral maps are mailed to the right holders for their further information and acceptance. In cases of disputes or detected errors, the right holders are entitled to submit objections, which should be 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).

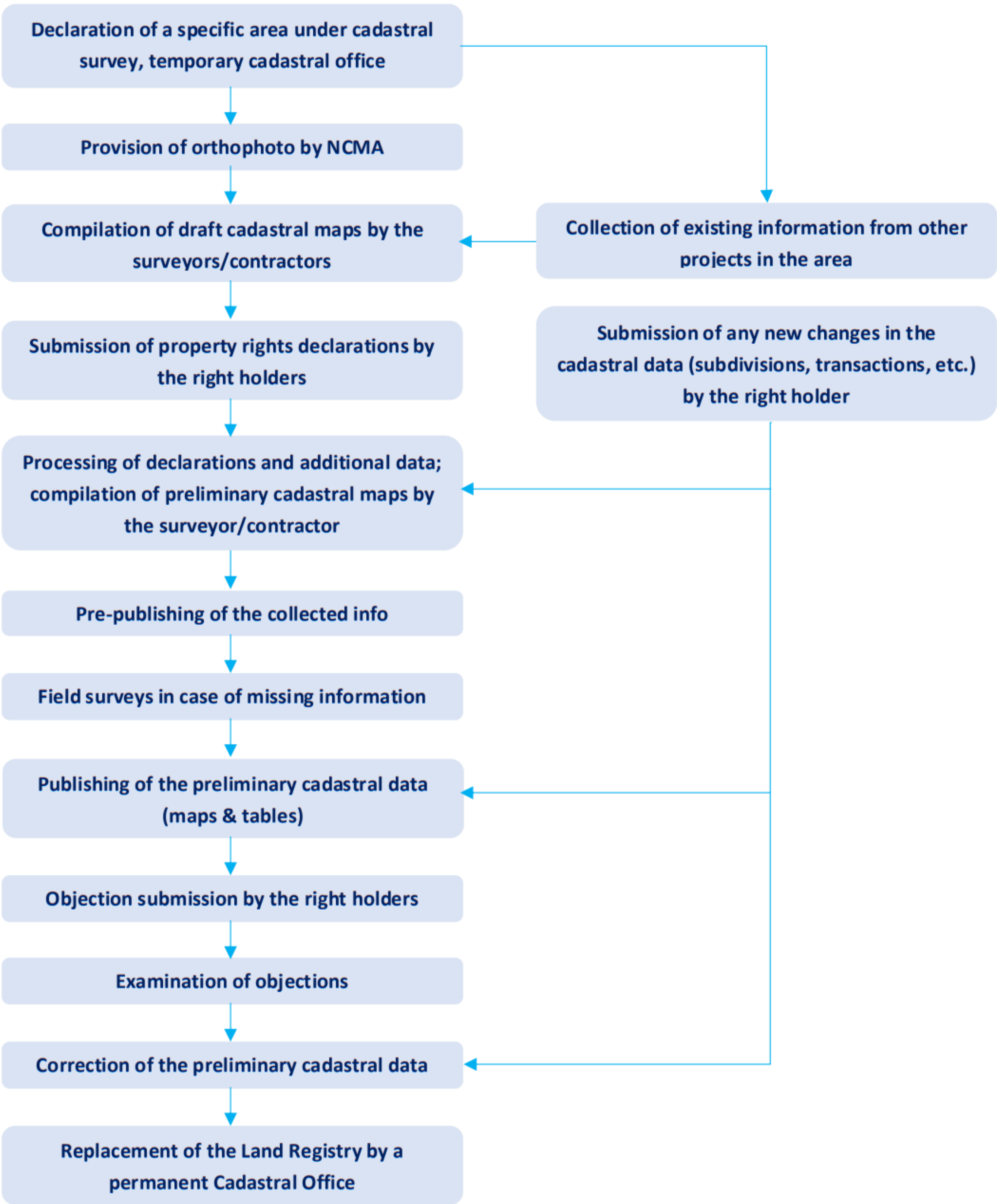


Figure 85. Official procedure of the Hellenic Cadastre.

5.5.1.2 Current Legislation

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.

The legislation about the registration of rights in the HC is consisted by a series of laws. The HC was established with the Law 2308/1995 (Government Gazette A΄, 114/15-06-1995), describing the process of cadastral surveys, while its operation was enacted by the Law

2664/1998 (Government Gazette A΄, 275/03-12-1998). These laws were amended successively by the Laws 2508/1997 (Government Gazette A΄, 124/13-06-1997), 3208/2003 (Government Gazette A΄, 303/24-12-2003), 3127/2003 (Government Gazette A΄, 67/19-03-2003), 3212/2003 (Government Gazette A΄, 308/31-12-2003), 3481/2006 (Government Gazette A΄, 162/02-08-2006) and 4164/2013 (Government Gazette A', 156/9-07-2013). The objective of these amendments, was to gradually adapt the legislation for the HC to the requirements of the project, as they emerged from the implementation experience (HellenicCadastre, 2022).

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. Apart from the horizontal properties, another type of composite ownership encountered in Greece is vertical ownership, based on Decree-Law 1024/1971. Vertical ownership separates the land parcel in such a way that each building that has been erected or is planned to be erected in each of its individual part, belongs or will belong to one or more of the co-owners of the shared land parcel, consisting an individual property. Vertical ownership can be further subdivided in condominiums, constituting a composite vertical ownership.

The introduction of the Civil Code, cease 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 HC, these types of customary properties are defined as Special Real Property Objects (SRPO) (Dimopoulou, 2015).

Nevertheless, despite the legal or customary definition of the 3D extend of these real property rights, their identification in the HC remains in 2D. In the case of horizontal property, which is usually recommended by a relevant notarial deed, is entered in the cadastral database with the form of descriptive information (e.g., building number, shared property number, floor, area, use, permit year, coordinates). Similarly, in the vertical properties with erected buildings, only the necessary descriptive information is entered in the cadastral database (e.g. the number of the building, the number of the vertical property, the total of the floors, the area of the vertical, use of the vertical property, year of permission). It is noted that in both cases, the cadastral diagrams do not present the 2D building outlines, but only the 2D outline of the 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, based on 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 Civil Law jurisdictions there is no 3D real property legislation established, and 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 survey plans, 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, 2020).

The Law 4412/2016 (Government Gazette A΄, 147/08-08-2016) harmonizes with the provisions of the Directives 2014/24/eu and 2014/25/eu, regarding to which the 'Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar'. However, these provisions had not 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 to the fore again with the Law 4723/2019 (Government Gazette A΄, 134/9-8-2019), which updates and replace the National Digital Strategy with the Digital Transformation Book. The Digital Transformation Book is published by the 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 of the economy, defining the specific principles governing each initiative. Thus, in 2021 with the Decision 40072/1492 of the Greek Ministry of Environment and Energy - General Secretariat for Spatial Planning and Urban Environment, a Support Group consisted by experts aiming to promote the European tool of BIM, was established. This step is very important for the modernization of the public and private procedures, paving the way for the future implementation of a 3D Cadastre in Greece.

5.5.1.3 Technical specifications of the mapping agency

The most recent technical specifications regarding the geometric accuracy of the cadastral surveys are declared in the 15649/31-3-2016 decision of the Minister of Environment, Energy and Climate Change and was published in the Official Government Gazette B΄, 923/31-3-2016. This decision was amended with the 141/20/27.5.2021 decision of the board of the HC's Directors and was published in the Official Government Gazette B΄, 2673/24.6.2021, however the specifications concerning the required geometric accuracy remained unchanged.

As Reference System (RS) the Greek Geodetic Reference System 1987 (GGRS87) is utilized, with the ellipsoid of GRS 80 and semi-major axis a=6378137.000 and flattening 1/f = 298.257222101. The GGRS87 is almost identical to the WGS84 RS, which is utilized by the GPS as RS. An approximate the transformation between the two systems can be achieved based on the following fixed parameters: $\Delta X = -200$ m, $\Delta Y = +74$ m, and $\Delta Z = +246$ m.

In terms of the provided orthophotos, the geometric accuracy varies according to their spatial analysis. The true color, digital, long-scale orthophotos (Large Scale Orthophotos-LSO), which were captured the time period of 2007-2009, cover the entire area under cadastrsl surveys and have geometric accuracy: RMSEx ≤1.00 m, RMSEy ≤ 1.00 m, RMSExy ≤ 1.41 m, and absolute accuracy ≤ 2.44 m for 95% confidence level. Additionally, true color digital orthophotos are also provided, with a spatial resolution of 20cm (Very Large Scale Orthophotos-VLSO), for the time period of 2007-2009, covering large urban centers. They are fully rectified images and include, except for the ground surface, all technical constructions (buildings, bridges, technical works, etc.). In terms of geometric accuracy of orthophotos these are: (i) RMSEx ≤ 0.20 m, RMSEy ≤ 0.20 m, RMSExy ≤ 0.28 m with absolute accuracy ≤ 0.48 m for 95% confidence level, for ground points, and (ii) RMSEx ≤ 0.40 m, RMSEy ≤ 0.40 m, RMSExy ≤ 0.56 m with absolute accuracy ≤ 0.97 m for 95% confidence level, for buildings' roof points.

The geometric accuracy of the cadastral diagrams is checked by comparing the coordinates of known reliable points, measured through highly accurate field surveys, with the respective ones depicted on the resulted cadastral diagrams. The accepted geometric accuracies are differentiated, based on the examined area. Thus, the geometric accuracy is RMSEx ≤ 0.50 m, RMSEy ≤ 0.50 m, RMSExy ≤ 0.71 m, while the absolute accuracy is ≤ 0,98 for 95% reliability in urban areas. Similarly, the geometric accuracy is RMSEx ≤ 1.00 m, RMSEy ≤ 1.00 m, RMSExy ≤ 1.41 m, while the absolute accuracy is ≤ 2.45 for 95% reliability in rural areas.

Besides the specifications concerning the geometric accuracy, there is another geometric control process that should also be mentioned. This concerns the Geometric Compatibility of the land parcel, as it is implemented on the ground, in relation with the data registered in the digital cadastral database. In order the declared data to be accepted, two main conditions should be met: (i) Compatibility of relative position and shape, and (ii) Area compatibility. Compatibility of position and shape exists when the buffer zone, that is located between the internal and the external boundaries of a land parcel, does not exceed 0.50 m in urban areas and 2.00 m in rural areas. Additionally, area size compatibility exists when the absolute difference $\Delta E = \left| E - E_{\Delta} \right|$ between the measured area for cadastral purposes (E) and the declared area by the landowner, according to his rights and topographic diagrams (E_{Δ}), is less or equal to the maximum acceptable are deviation (Δ_A), i.e. when $\Delta_E \leq \Delta_A$.

Through the examination of the abovementioned technical specifications of HC, it appears that required geometric accuracy of the collected data is not very strict and thus alternative data capturing techniques, besides traditional highly accurate procedures, may be also utilized. Recent research results have shown that the achieved accuracy of crowdsourced data can meet these specifications, highlighting crowdsourcing as a relatively useful and reliable data capturing technique (Basiouka & Potsiou, 2012b; 2014; Basiouka, 2015; Mourafetis et al., 2015; Gkeli et al., 2016; Jones et al., 2017; Apostolopoulos et al., 2018; Cetl et al., 2019; Potsiou et al., 2020; Mourafetis & Potsiou, 2020). However, this fact does not limit the improvement of the accuracy of the crowdsourced cadastral data in a later stage.

5.5.2 The Hellenic Crowdsourced Workflow

The developed methodology aims to provide an alternative crowdsourced cadastral solution 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 implemented yet. As the developed crowdsourced methodology concerns the phase of the initial 2D and 3D cadastral data acquisition, the first seven (7) stages of the official HC procedure are modified and replaced with those of the developed crowdsourced workflow; while the rest five (5) stages of the HC process, are maintained unchanged. The main idea of this effort is to declare the whole territory of Greece under cadastral survey and to proceed with the overall recording of the 3D crowdsourced cadastral information in a comprehensive standardized (LADM-based) cadastral database. The overview of the proposed process is presented in Figure 86.

The first phase of the crowdsourced methodology for Greece, starts with the compilation of a draft registration basemap, through collecting all the available cartographic/ geospatial (orthophotos, cadastral diagrams, architectural plans, aerial photos etc.), 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 rights 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.

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 rights holders through the cadastral mobile application. Each right holder, identify his/her property on the available basemap or select it on the available BIM/IFC representation, and insert all the necessary cadastral information. In cases where the 2D HC is implemented in the current study area, the cadastral diagrams and maps, should be utilized as guide for the implementation of 3D cadastral surveys. Otherwise, the necessary 2D cadastral data regarding the boundaries of the land parcels, the buildings outlines and the building unit (i.e. apartment) should be first collected, in order to proceed with 3D registration. 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, 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 (Figure 86). Next, the preliminary cadastral data is published at the NCMA's offices, while then the examination of objections and the correction of data, is compiled. By the end of the phace, these registrations constitute the Initial/First Registrations in the 3D Hellenic Cadastre. Finally, the existing Land Registry Offices are replaced by permanent Cadastral Offices.

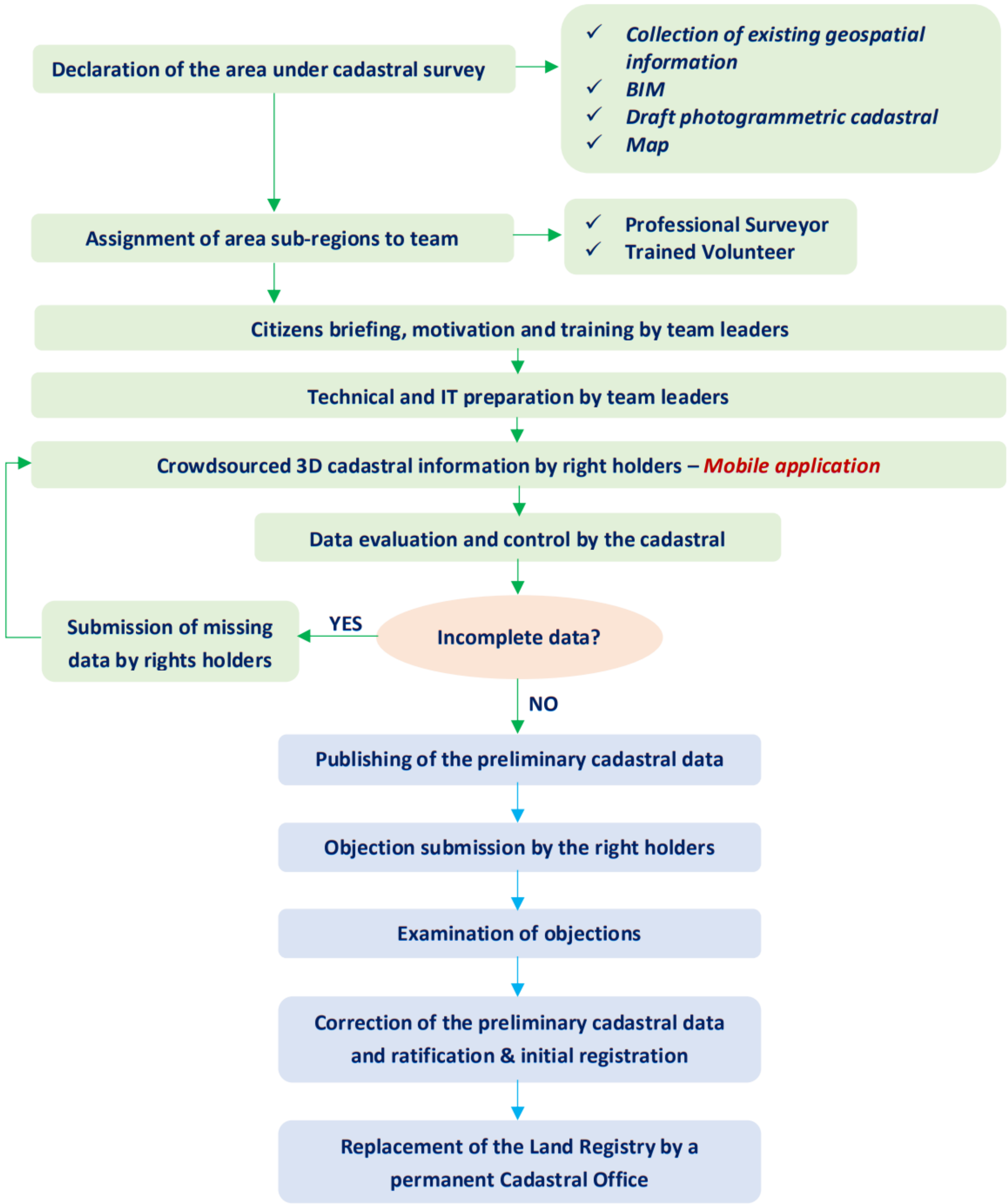


Figure 86. Proposed crowdsourcing methodology for 3D cadastral surveys in Greece.

5.6 Conclusions

The developed methodology aims to provide an alternative crowdsourced cadastral workflow for the initial implementation of 3D Cadastres, even in areas with incomplete or without a 2D land registry. The main objective is to reduce time and costs, and to simplify the most expensive and time-consuming phase of cadastral registration process, which is the cadastral data acquisition.

A brief presentation of the main elements around which the methodology was tabulated, organized and developed has been given, aiming to highlight their importance. The introduction of citizens' participation in 3D cadastral procedures, the establishment of briefing and training sessions as well as the infield active support by team leaders, consist key features in increasing the reliability of the collected 2D and 3D data, while reducing the required time and human resources of the process. Through exploiting the available geospatial infrastructure of each country, integrating various spatial data sources from other application areas, standardized data models, low-cost modern technologies and data capturing techniques, the flexibility and exchangeability of the proposed methodology is accelerated.

Besides the detailed description of the individual methodological phases, a more concrete crowdsourced workflow targeting the Greek territory is presented. A brief presentation of the Hellenic Cadastre project has been conducted, aiming to show how it works, its technical specification and the legal framework defining its function, in order to provide some conclusions regarding any existing provisions concerning the 3D aspect and the potentials of integrating the proposed methodological framework into the existing HC procedure. As turned out, there is no 3D real property legislation established. The only reference regarding the third dimension arises through general descriptions about the conceivable spatial extend of the property units, which usually is determined more precisely through a notarial deed. This applies not only to Greece but also to several other countries, with result the need for the immediate implementation of a reliable 3D cadastral system to become imperative.

The main remarks of this chapter are summarized below:

- The developed methodology consists a pioneer approach, as it is the first attempt introducing crowdsourcing in 3D cadastral surveys.
- The proposed process consists of a series of simple and flexible stages, which can be completed with the aid of new technologies, by non-professionals.
- The establishment of a two-way model of cooperation between right holders/citizens, volunteers, technicians, experts/surveyors, inspectors and the national mapping agency, speed up the implementation processes and increase their reliability.
- The exploitation of various 2D and 3D data sources as registration background, increasing the flexibility and the adaptability of the methodology to the current needs, legislation and proprietary situation of each country, both in developed and developing world.
- The proposal of introducing low-cost technologies and innovative data capturing techniques, in 3D cadastral surveys, keeps the financial resources low while exploit alternative 2D and 3D data sources.
- Through the integration of LADM standard, a common communication language can be established, enhancing the exchangeability of data both between the involved parties within the same country as well as between different countries.

Chapter 6

Technical Systems Configuration

Ideally a 3D cadastral platform should enable archiving, visualization, queries, analysis of 3D structures and the corresponding cadastral information on different temporal time-stamps. Until now, 3D systems focus on 3D modelling of physical real-world objects (building), without paying much attention to their multi-dimensional implementation (Jaljolie et al., 2016). The worldwide efforts trying to establish 3D Cadastres have been made significant progress, however the immediate implementation of such a system is still far from be realistically achieved. Although the Land Administration Model (LADM ISO 19152) (ISO, 2012) set the basis for 3D cadastres, there are still several aspects that need to be further investigated and improved both technically and legally (Oldfield et al., 2016).

The developed technical framework aims to exploit the current initiatives of the scientific community and provide a modern technical solution for the initial acquisition, registration, management, storage, maintenance and updatance of a large amount of 3D crowdsourced cadastral data. This effort aims to enhance the procedure and reduce the costs of 3D cadastral surveys, by exploiting the potentials of modern technologies, data sources, IT tools – like mobile devices (smartphones or tablets) – web services, database management systems (DBMS) services, in combination with low-cost open-sourced software, for the compilation of the initial implementation of 3D cadastral surveys and the generation of a preliminary 3D cadastral database directly by the right holders.

In this Chapter the overview of the architecture of the developed technical system; the detailed description of the sub-systems; and, how all the included parts work together in synergy, is described and presented. Next, the introduction of the LADM ISO specification in the developed system is realized, through the development of the database schema for the management and storage of the collected 3D crowdsourced data. The main objective of this venture is to provide an integrated solution able to structure and manage different data types into the same platform. Finally, the main conclusions regarding the developed technical system are presented. It is noted that 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.

6.1 Overview

The main components of this technical solution are the two complementary sub-systems which may be referred 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, while the communication 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 Figure 87.

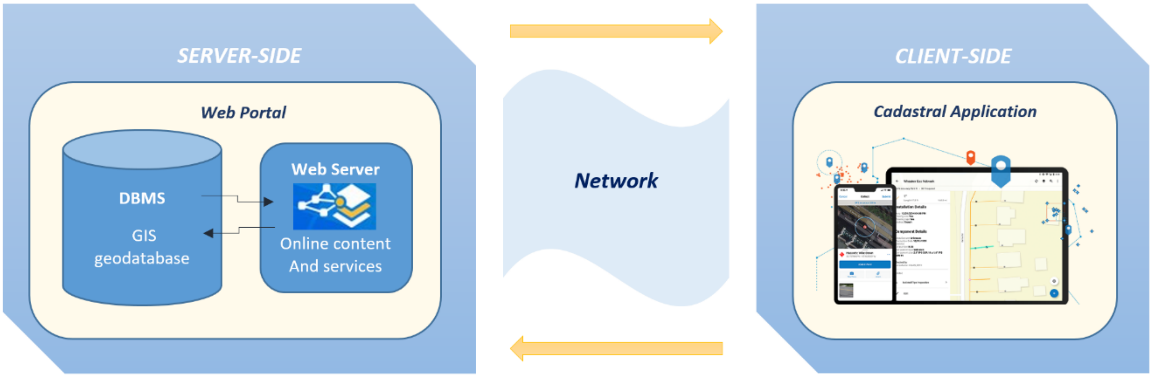


Figure 87. Server-client system architecture diagram of the 3D cadastre technical framework.

In this doctoral dissertation the utilization of a mobile application and therefore of a mobile device, as the main data capturing tool, is preferred and selected. However, the potential use of a web application through a desktop computer is also explored, in cases of high quality 3D data availability (e.g. BIM data).

6.2 3D Mobile Application

To support the client-side of the technical framework an open source prototype for Android mobile devices is developed by the author of this dissertation. As cadastral-oriented mobile applications are limited especially in regards to the third dimension, this application is pioneer consisting the first practical attempt to approach this research domain in the light of crowdsourcing. The developed mobile application aims to assist the implementation of 3D cadastral surveys, through the integration of various technical elements and tasks, including:

- the active participation of the right holders or other non-professionals;
- the identification and collection of 3D geometric and descriptive data, utilizing the available 2D or/and 3D geospatial information;
- the automatic generation of 3D land parcel and property unit models as block models (LoD1), using Model-driven approach – when needed;
- the generation of the corresponding KML objects (land parcel, building unit) – when needed;
- the registration of the cadastral data and their relationships within a 3D (LADM-based) cadastral geodatabase;
- the visualization of 3D cadastral objects in real-time, on the mobile phone's screen.

6.2.1 Software tools and technical declarations

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 following set of software tools are utilized:

(i) the Integrated Development Environment of Visual Studio 2013 (IDE);
(ii) the Java Deployment Package Oracle JDK 8 (Java Development Kit);
(iii) the Android SDK Manager (for API level 19);
(iv) 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);
(v) 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;
(vi) the SharpKML library;

(vii) the Server of ArcGIS Online (cloud of ESRI), for the storage and management of data (ESRI, 2022); and

(viii) the programming language of C# are utilized.

The application is initially developed and tested on an Android 4.4 mobile device with API level 19 and a 5.25 inches' screen, but it can also be adjusted to other Android devices with different technical characteristics (e.g., other mobile phones, tablets, etc.). Besides the screen size, the application enables zoom to reach high accuracy requirements, with the maximum supported level of scale to be about 1:100, allowing the user to have a more detailed observation of the basemap and the 3D digital environment.

As reference system of the basemaps the GGRS87 (Greek Geodetic Reference System 1987), is used. For the data storage, the Server of ArcGIS Online is used and then data are pulled from the application if there is an Internet connection. While saving, the data are projected in the Web Mercator Auxiliary Sphere, which is used by the ArcGIS Online as reference system. Furthermore, all the utilized data are adjusted to a Digital Terrain Model (DTM) offered by ESRI (ESRI, 2022), allowing the application to simulate the 3D real world. These transformations are essential in order the generated block models (LoD1) to be correctly visualized in the 3D scene.

6.2.2 Development Stages

6.2.2.1 Version 1

In the first stage of the development a GIS interface is formed, enabling the visualization of the available 2D cartographic basemaps (orthophotos, 2D architectural floor plans etc.), the identification of the property boundaries on the current basemap, the insertion of the necessary geometric and descriptive information regarding the property and the right holder, and the 3D visualization of the declared properties.

Launching the application, the GPS sensor of the mobile device is required to provide information regarding the user's position. In case that the GPS sensor is inactive, a warning window appears, prompting the user to activate it (Figure 88). If the GPS sensor is active, continuous updates for the user position are received from the Location Services, which appear on the screen both quantitatively, with the geodetic coordinates of the position and their accuracy with 68% confidence level, as well as graphically displaying the position on the basemap (Figure 89c). However, the GPS sensor is used only for a rough positioning in order to avoid gross errors during right holder's orientation in 3D space.

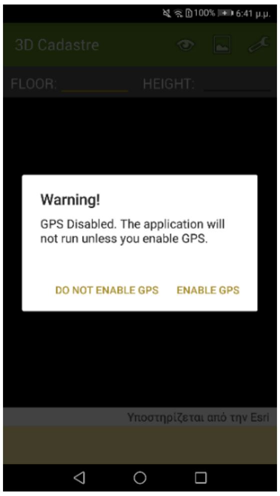


Figure 88. Mobile Application Interface - Warning window, prompting the user to activate the GPS.

The user is able to browse several different basemaps using the selector basemap tool, depicting either the orthophoto of the area or the architectural floor plans of each building. The application provides a set of tools for the identification of the property boundaries and the insertion of the necessary proprietary information for the declaration of the property rights. The user/right holder may define the boundaries of the property upon the basemap by digitizing the corners of the polygonal boundaries on the basemap: first the land parcel property boundaries and then the property unit boundaries utilizing the digitization tool. The user may then insert additional data about the personal information of the right holder, the type of the property rights to be declared and any additional comments regarding those rights. In addition, the user is able 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 (Figure 89).

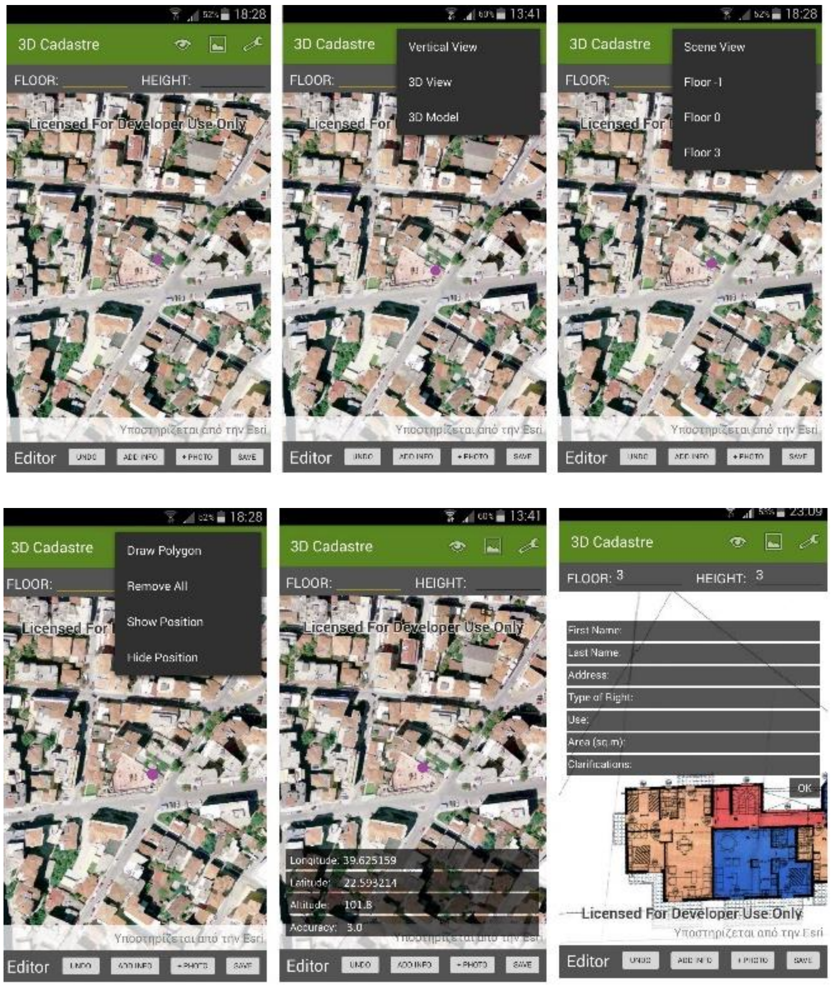


Figure 89. Overview of the developed application supporting the proposed crowdsourcing procedure for initial registration of 3D cadastral data. (a) The mobile application's user interface (b) tools for adjusting the viewing mode of the scene (c) basemap selection tools (d) polygon drawing tools (e) representation of GPS coordinates (Show position tool) (f) representation of input information fields (ADD INFO).

Furthermore, 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 are 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 3m. Once the data are imported in the application and checked by the rights holder, the 3D property unit model is automatically produced based on the inserted geometric (polygonal) and numeric information (height, floor) following a parametric modelling approach. Simultaneously, the corresponding 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) are visualized on the mobile's phone screen, both above and/or below the ground surface. As the environment of ESRI does not allow the visualization of objects located below the ground surface, a different approach is followed. More specifically, the 3D models are elevated at a relative altitude above the ground, accompanied by a transparent surface simulating the ground level. 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.

6.2.2.2 Version 2

In the second stage of the development, the interface of the mobile application is appropriately configured in order to lead and simplify the registration procedure, while it is modified so to be able to automatically be adjusted to mobile devices with varying screen sizes (Figure 90). Beyond its previous capabilities, the application enables the registration of the cadastral data and their relationships within a LADM-based cadastral geodatabase. The type of the required descriptive information is differentiated aiming to include the necessary information as determined by the LADM standard. For this technical development the descriptive information about the building (area code, address), the right holder (name, role, type of rights) and the property/building unit (floor, height, use, area size, volume) are selected.

Furthermore, the application is enriched with additional geometric tools able to assist the registration procedure in adverse cases of weak basemap availability. In complex cases where the parcel boundaries are not clearly recognized in the field (e.g., not spotted on the ground, as legal boundaries that are not materialized in the field but 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 application provides a set of additional geometric tools facilitating their identification and digitization. These geometric tools implement geometric constraints through simple geometric shapes and processes, utilizing inserted numeric data (in meters), provided by the user. Through exploiting visible basemaps' features, as reference features, and geometric information of proximity, similarity, continuity, enclosure or even symmetry between them and the desired boundary features, provided by existing architectural plans, deeds etc., the gradually identification and digitization of proprietary boundaries is feasible.

The developed application provides the user with a geometric editor which comprises all the available geometric tools and operations (Figure 91). The developed geometrical tools include (Figure 5): two (2) circle drawing tools; two (2) line segment drawing tool; a parallel-lines drawing tool, at a certain distance from a specific line (full offset); a drawing tool of vertical lines of certain length on either side of a specific line; and, three tools for determining intersection points between 2 circles, a circle and a line, and 2 lines. The user may start or pause the cadastral registration procedure, performing any necessary geometric operation, in order to identify features (point or linear) representing the boundaries of his/her property. When the user detects the desired feature through this process, he/she may select it by tapping it on the screen, and then continue with the registration procedure.

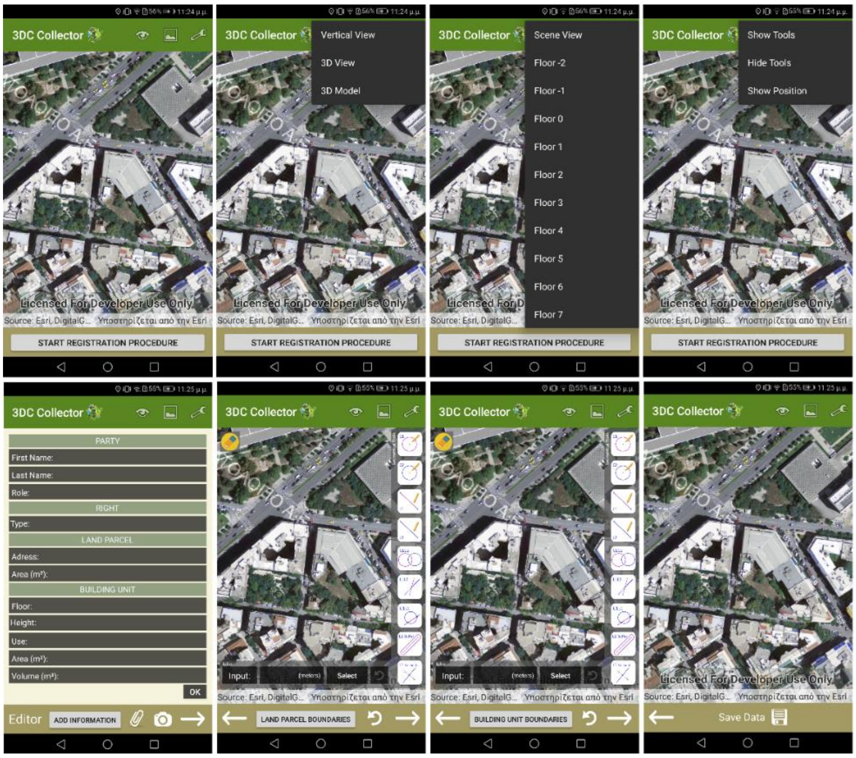


Figure 90. Users interface overview of the developed mobile application.

Figure 91. Geometrical drawing tools offered by BoundGeometry application. Top (left to right): circle, line, offset to line, vertical lines Bottom: intersection points between 2 circles, 2 lines, a circle and a line.

6.2.2.3 Version 3

In the third stage of the development, the mobile application is being upgraded, adding to the current operations the potential of manipulation and visualization of BIM/IFC data – when they are available. The user is able to choose from the menu of the application whether or not she/he is going to proceed with the 3D registration, utilizing either the existing 2D cartographic basemaps or the BIM (Figure 92).

If BIM data describing user's property unit is available, the user may proceed with the cadastral registration process (Figure 92). The user may navigate throughout the 3D scene, locate his/hers property unit on BIM and select it, by tapping it on screen. Following, the user may enter all the necessary cadastral information included in the information form, through the add information tool. 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 (Figure 92). Finally, the user can store the collected data in the cadastral database, updating the system with the new records corresponding to the 3D property unit model, provided by the BIM.

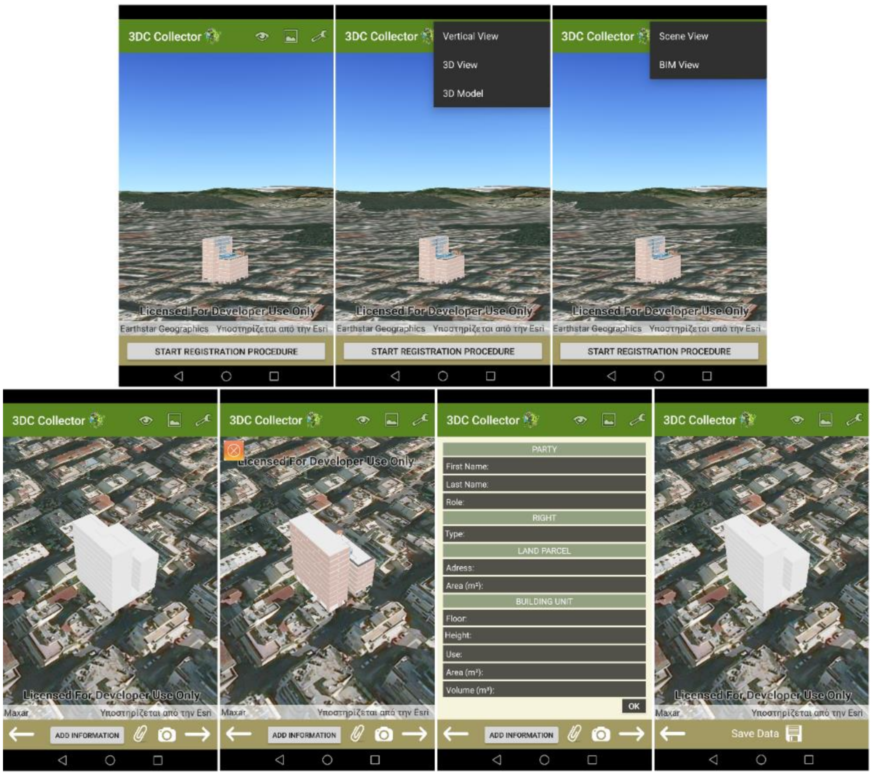


Figure 92. Users interface overview of the developed mobile application.

6.2.2.4 Version 4

In the fourth stage of the development, the mobile application is optimized, integrating the functionalities of all the previous versions into a unified form. The 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, when available (Figure 93). Through selecting the desired option, the user may proceed 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, the attaching of other useful documents (e.g., plans, deeds etc.). Furthermore, the user should provide numeric information through the "Height" and "Floor" fields, defining the height 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.

If the user proceeds with the Manual selection option for cadastral registration (Figure 94), 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 land parcel's and building unit's boundaries on the available basemap. In complex cases where the land parcel's or the building's unit boundaries are not clearly recognized in the field, the geometric tools provided by the mobile application may also be utilized.

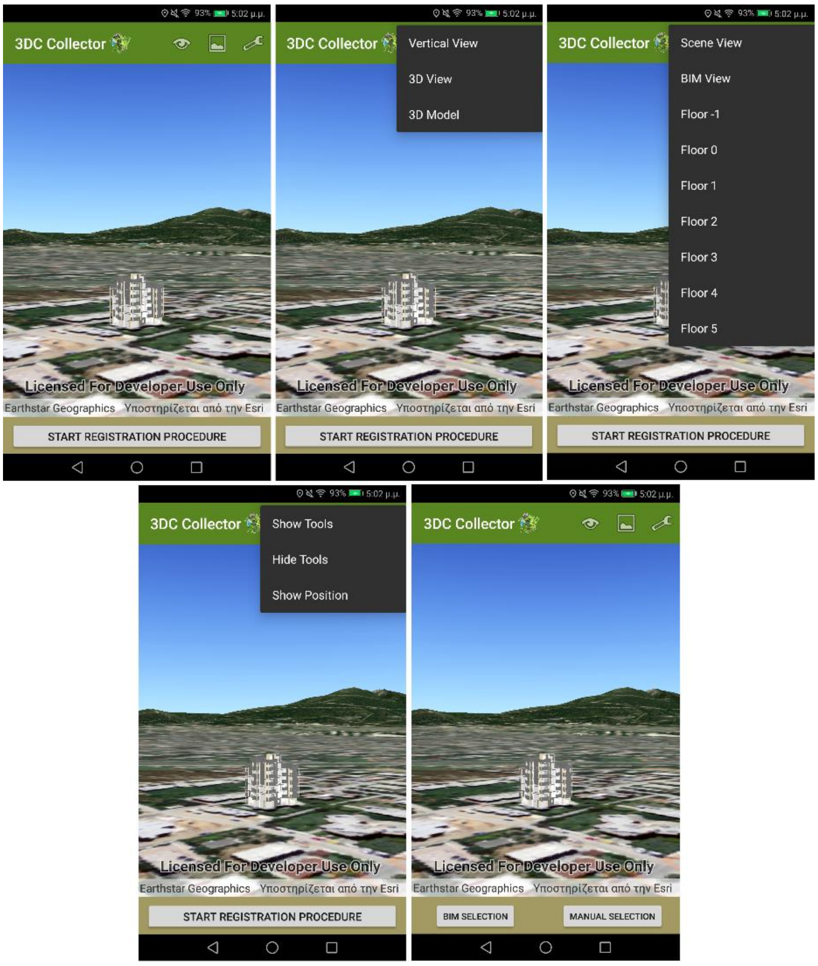


Figure 93. Users interface overview of the developed mobile application.

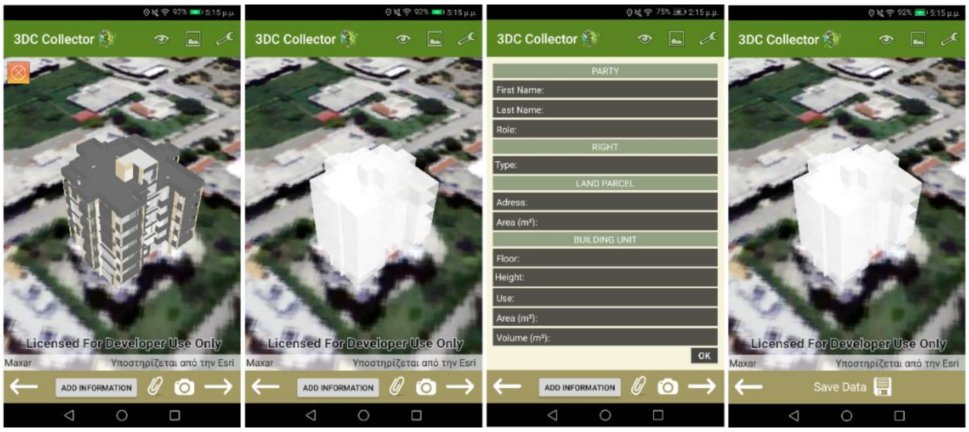


Figure 94. Users interface overview of the developed mobile application.

Otherwise, if BIM data describing user property unit is available, the user may proceed with the BIM selection for cadastral registration (Figure 95), and therefore locate the desired property unit on the BIM, select it by tapping it on the screen and enter all the necessary cadastral information. During this 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 (Figure 95).

Finally, regardless of which option the user may choose, he/she 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.

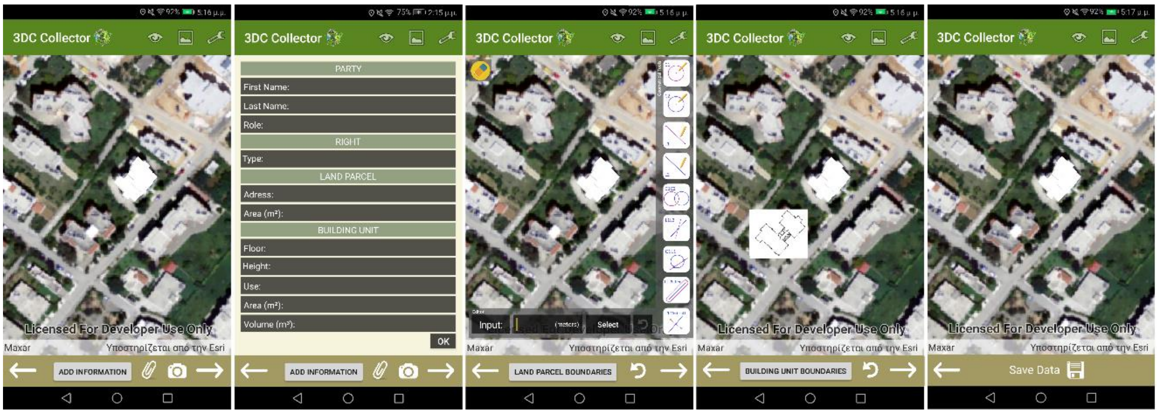


Figure 95. Users interface overview of the developed mobile application.

6.3 3D Web Application

Besides the application for mobile devices, a web application is also developed as a potential alternative for the integration of BIM/IFC data into a GIS environment able to support the 3D crowdsourced cadastral framework. The web application may not have the same capabilities with the mobile application, but offers some essential tools needed for viewing and manipulating the available BIM data as well as for collecting, storing and updating the 3D cadastral data regarding the properties RRRs and the right holders. Furthermore, the application is enabled to add new or update already existed registrations and relationships within an LADM-based cadastral geodatabase.

6.3.1 Software tools

For the development of the web-based application, the following set of software tools was utilized:

- (i) the web development environment of CodePen (CodePen, 2021);
- (ii) the ArcGIS API for JavaScript 4.18 of the ESRI, adding the function of ArcGIS to the application via libraries with a wide variety of methods and functions;
- (iii) the HTML and JavaScript programming languages; and
- (iv) the Server of ArcGIS Online (the ESRI cloud) for the storage and management of data (ESRI, 2022).

BIM data are translated in IFC format and then converted into a geodatabase, enabling their further manipulation from the web application. Similarly with the mobile application, the data are projected to the Web Mercator Auxiliary Sphere, which is used by the ArcGIS Online as reference system. The displayed scene simulates the real world using a Digital Terrain Model (DTM) provided by the ESRI (ESRI, 2022). It is noted that the selection of the ESRI product consists of only a first attempt at the implementation of our approach. Other open-source platforms for software applications could also be utilized.

6.3.2 Development Stages

The development of the web application, started with the configuration of a user-friendly interface, aiming to enable its usage by non-professionals (Figure 96). The physical cadastral spaces are presented in Level of Detail 3 (LoD3), while legal cadastral spaces are presented in LoD1, defining the full extent of the declared RRRs. The 3D models may be overlaid on the available spatial infrastructure as 2D architectural plans, orthophotos, aerial photos, Open Street Maps, etc.

Figure 96. Overview of the user interface of the developed web application.

The application enables the user to navigate through the 3D scene, formed from BIM data, in order to be oriented and be able to identify his/her property in the model. The user interface represents the 3D building scene and provides a set of functional tools enabling the user to move throughout the scene, zoom in/out, and proceed with 3D registration by utilizing several data manipulation tools (Figure 97). More specifically, the developed application provides the following tools:

(i) a layer management tool allowing the user to enable and disable a building’s layers presented in LoD1 or LoD3 in order to identify his/her property in the BIM;
(ii) a 3D measurement tool enabling the user to measure the length and calculate the area on/of 3D objects;
(iii) a building slicing tool al-lowing the user to create vertical and horizontal slices, revealing information about the building’s interior spaces; and
(iv) an editor tool enabling the user to select his/her property in the BIM, which is presented in LoD1—where the property is presented as a solid entity of a single ownership—and insert all the necessary descriptive cadastral information about his/her rights.

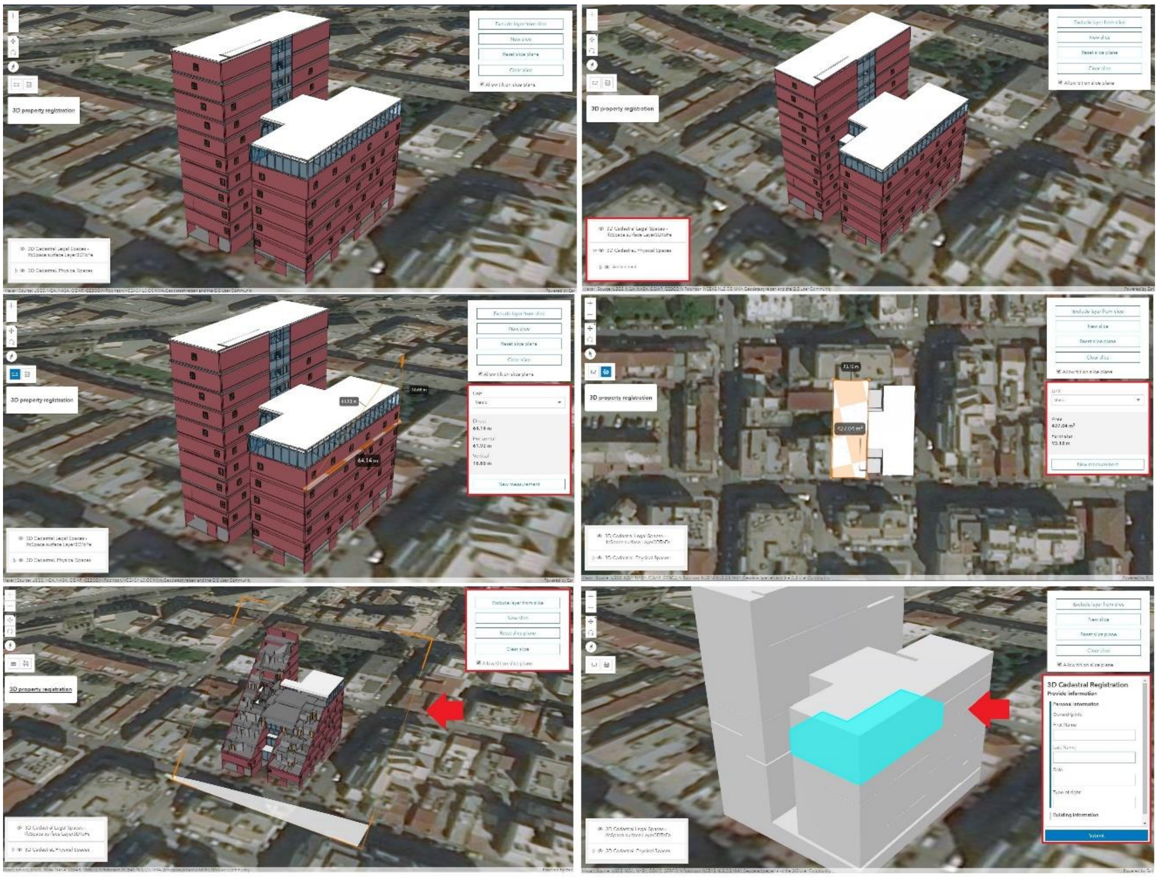


Figure 97. Top row (left to right): the application's interface and the layer management tool. Middle row (left to right) the 3D length measurement tool and the 3D area and perimeter measurement tool. Bottom row (left to right): the building slicing tool and the editor tool.

The web application may be utilized both for the creation of new registrations as well as for the submission of potential changes in the declared property rights (such as land/property use). Once the user enters all the necessary cadastral information, he/she may submit the declarations, updating with new records the LADM-based cadastral database. Thus, this process results in the creation of an up-to-date database, which may be further processed by the cadastral agency in order to proceed with the necessary evaluation and control of the submitted data.

6.4 DBMS Architecture

6.4.1 Software tools

For the server-side, three DBMS conceptual schemas supporting the different potential data types of the developed technical system, are generated through Enterprise Architect (EA) UML modelling tool by Sparx Systems. EA supports a range of open industry standards, simplifying the analysis, design, implementation, testing, and maintenance of several models using the Unified Modeling Language (UML) and other open standards. The use of Model-Driven Generation (MDG) Technologies supports the application of Geography Markup Language (GML) schemas and the UML profile for ArcGIS applications. Thus, EA enables the generation of geodatabase's conceptual schemas, empowering the development of GIS applications such the ones developed in this doctoral dissertation. As ESRI's ArcGIS software is selected for the further manipulation and management of the collected data, ArcGIS toolbox was utilized to form each of the application schema elements of LADM, in order the final model can comply with the ArcGIS workspace metamodel.

6.4.2 LADM-based DBMS

6.4.2.1 Version 1

The data structure of the database is based on the LADM standard, while some new classes were generated in order to support the geometry of 3D spatial units. Figure 98 presents the basic classes of LADM that were preserved: LA_Party, LA_RRR, LA_BAUnit and LA_SpatiaUnit as well as a new class named LandParcel3D. The insertion of the class LandParcel3D tends to emphasize the basic spatial unit element and inherits the attributes of LA_SpatiaUnit class, while an attribute defining the address was added.

According to LADM, a "true" 2D representation of a spatial unit consists of a boundary face string, known as LA_BoundaryFaceString, while a "true" 3D representation of a spatial unit consists of arbitrary oriented faces, known as LA_BoundaryFace. However, besides these definitions the identification of the acceptable 3D geometries and representations for the 3D cadastral objects is still challenging and thus several data sources may be further investigated. Ying et al. (2015) states 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. Furthermore, a polyhedron may be defined as a 3D solid composed of vertices, edges, faces and an incidence relationship between them (CGAL, 2019).

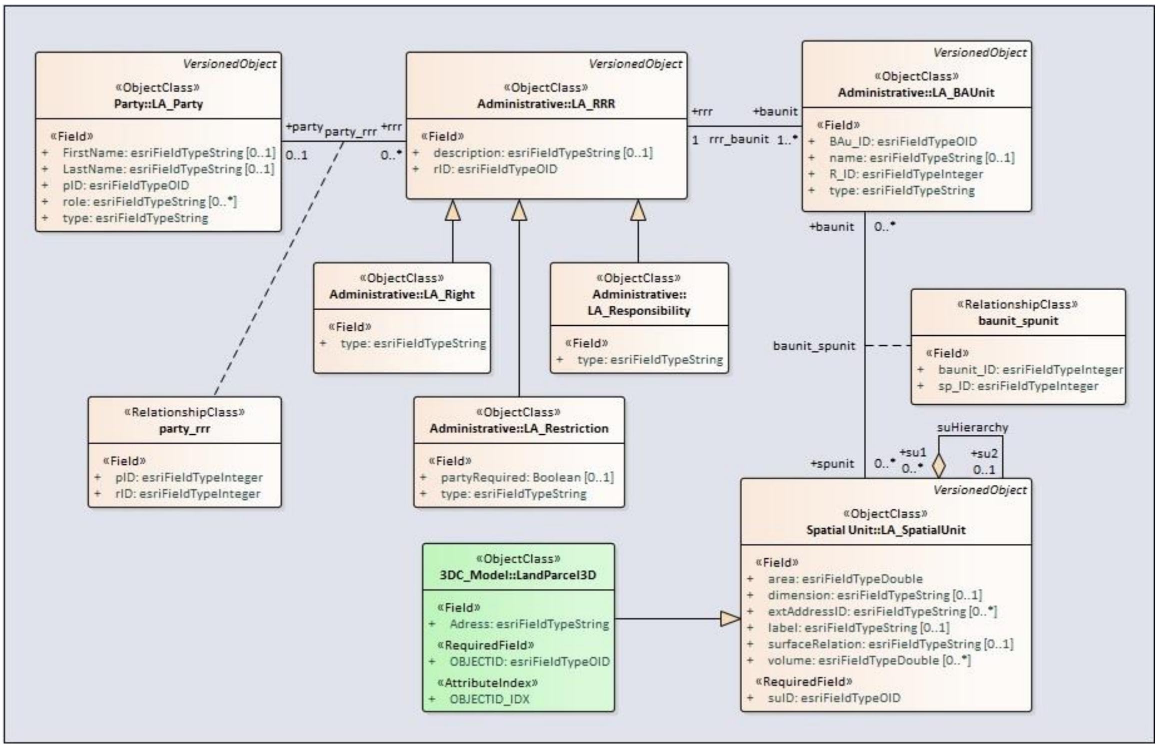


Figure 98. Conceptual schema of the developed data model.

Based on this point of view, the UML diagrams describing the structure of the 3D cadastral objects were created. Thus, a 3D land parcel may be defined as a set of connected polygonal faces, representing a 3D prismatic volume with no upper and lower bound. In Figure 99 the proposed model defining the structure of a 3D cadastral parcel is presented. 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.

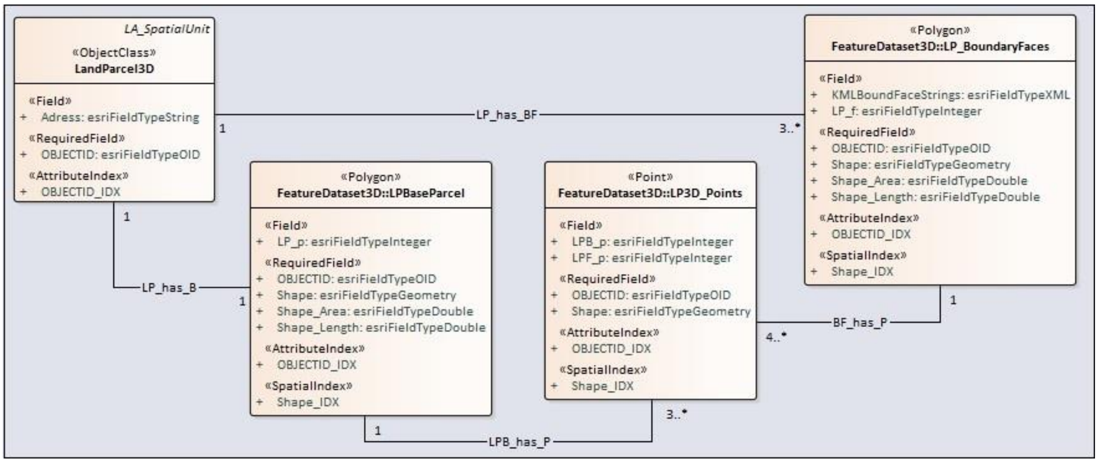


Figure 99. Proposed conceptual schema defining the structure of a 3D cadastral parcel.

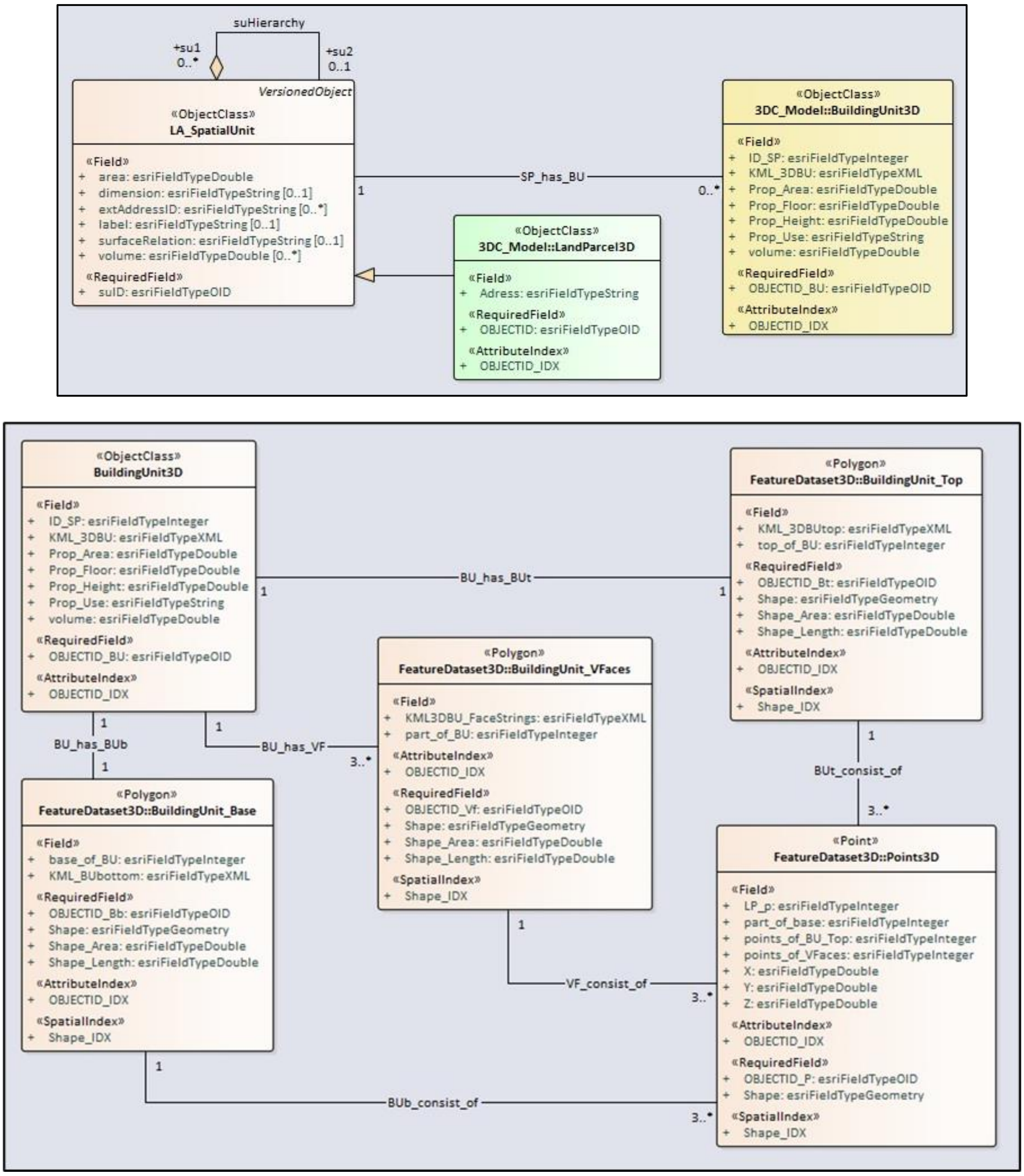


Figure 100. Conceptual schema defining the structure of a 3D cadastral building unit.

Similarly, in order to describe the 3D building units a new class named BuildingUnit3D was created. BuildingUnit3D class is directly linked with LA_SpatiaUnit class; it preserves the necessary information regarding the definition of the polyhedron geometry of a building unit (property). As such, the attributes related to the floor, height, area, volume of each building unit were selected. The attribute referring to the current use of a building unit was inserted as a descriptive characteristic. 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 properties can be registered correctly. Thus, a 3D building unit may be defined as a set of connected polygonal faces, representing a 3D prismatic volume with specified upper and lower bound. The proposed model defining the structure of a 3D cadastral building unit is presented in Figure 100. The classes BuildingUnit_Top, BuildingUnit_Base, BuildingUnit_VFaces and Points3D include the geometry describing each one of the building unit's face as well as the relationships between them. Similarly, with the class LP_BoundaryFaces, each one of these classes is represented by a KML object in order to simplify their representation in the ArcGIS platform.

6.4.2.2 Version 2

In the second stage of the DBMS's development, some minor changes were conducted aiming to optimize and simplify the database's schema, as well as to impart a geometric character to all the physical entities. The LA_SpatialUnit object class was transformed into an ArcGIS point feature class in order to be distinguished geometrically by the point representing its center. Likewise, BuildingUnit3D object class was transformed into an ArcGIS point feature class preserving its attributes. Furthermore, the LandParcel3D class remains connected to LA_SpatialUnit class, with a '1-1' association, aiming to reinforce the fact that they refer to the same element. Based on this, BuildingUnit3D class was connected with LandParcel3D class with '1-0..*' association, as each land parcel may have no or several different building units built on it. Figure 101, depicts the conceptual schema representing the relationship between LA_SpatialUnit, LandParcel3D and BuildingUnit3D classes.

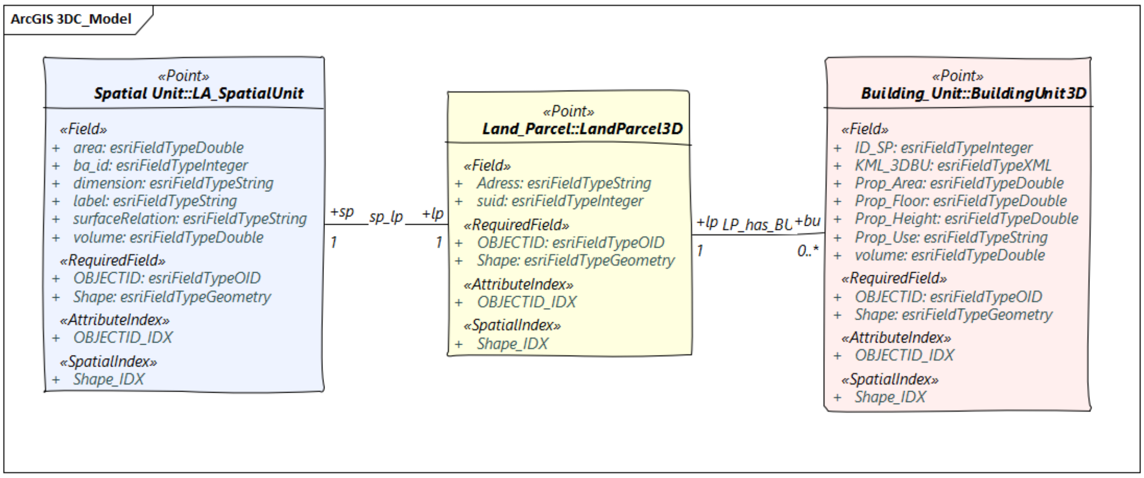


Figure 101. Conceptual schema defining the relationship between the classes: LA_SpatialUnit, LandParcel3D and BuildingUnit3D.

Beyond those alternations, all the previously developed classes representing the land parcel and the building unit geometric structure remain, incorporating the aforementioned differentiated classes (Figure 102 & Figure 103).

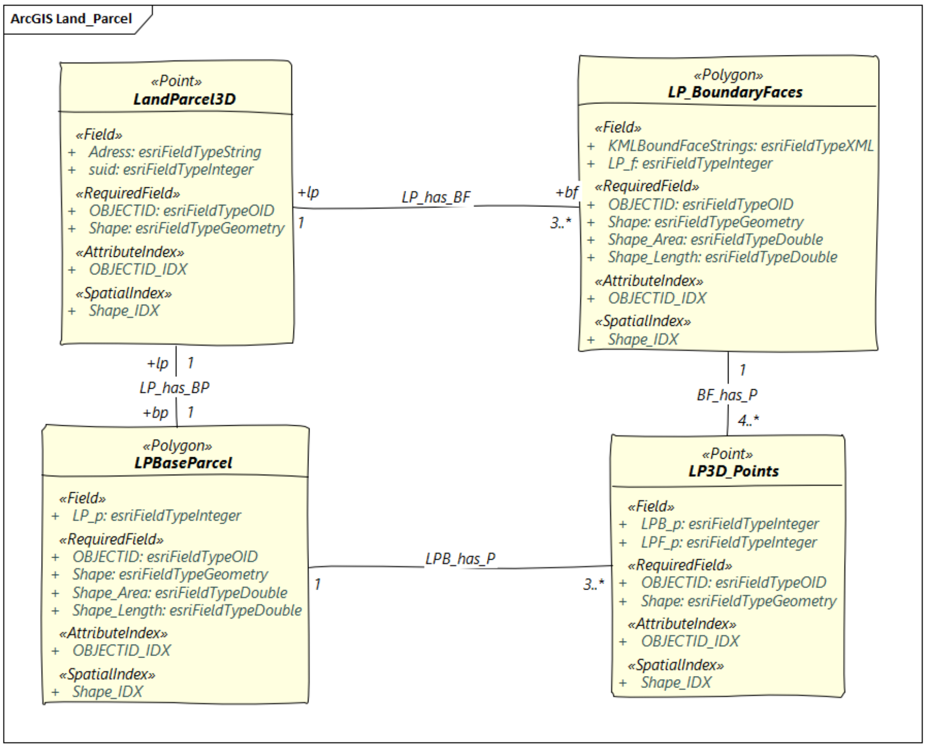


Figure 102. Proposed conceptual schema defining the structure of a 3D cadastral parcel

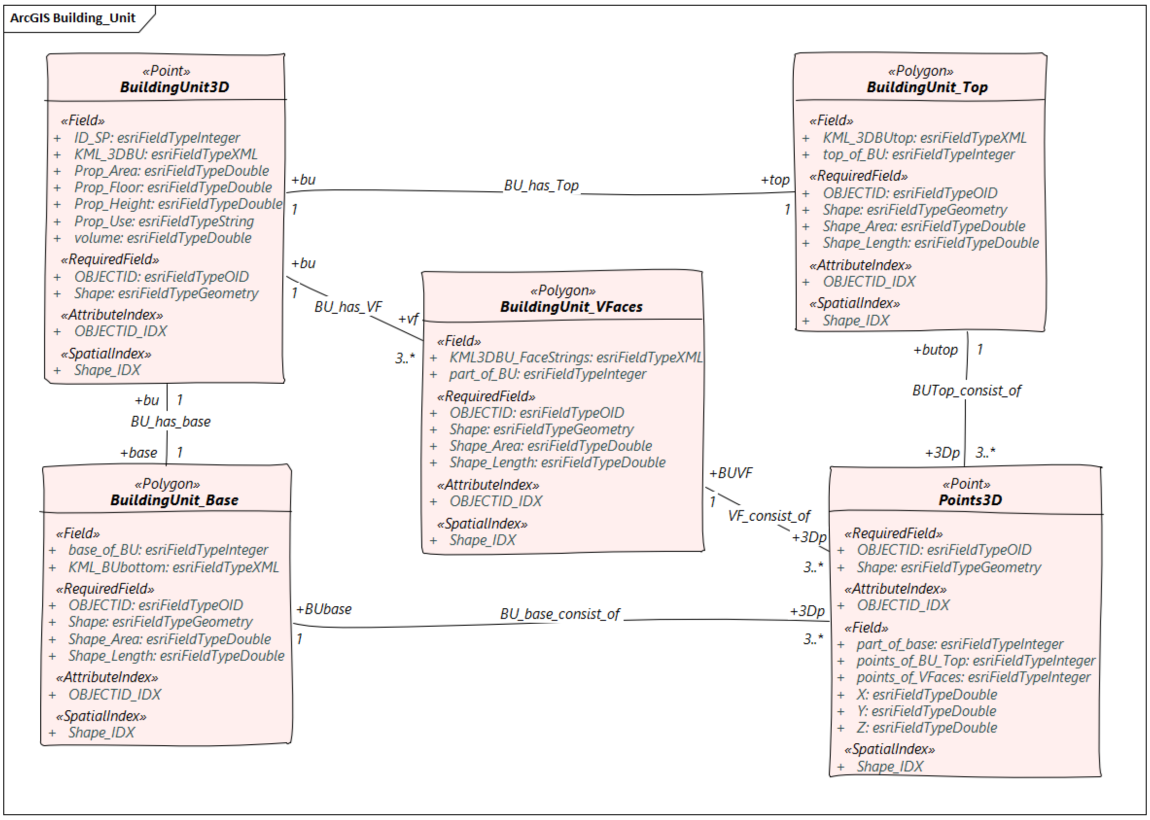


Figure 103. Conceptual schema defining the structure of a 3D cadastral building unit.

6.4.3 Integrating BIM/IFC schema with LADM standard

In the third stage of the DBMS's development, the developed DBMS conceptual schema was optimized in order to integrate the BIM/IFC aspect (Figure 104). In order to do so, some limitations concerning the linking process between BIM and LADM should be settled. BIM consists one of the most detailed and comprehensive object-oriented method of modelling buildings, providing in detail the geometry of the complex physical buildings' spaces, such as rooms, corridors, walls and floors. This may suffice to define the 3D cadastral physical spaces, but not the 3D cadastral legal spaces. A legal space needs to be related with only one space consisting the ownership boundary of a single property, where the corresponding RRRs are assigned. Thus, for defining the 3D cadastral legal spaces through BIM, a number of physical spaces should be united into single entity, which will describe the legal space of ownership rights. Thus, a 3D spatial representation derived from a BIM may present an apartment which spread across multiple rooms but belonging to one owner. With IfcSpace entity, the representation of volumetric cadastral spaces inside a building is feasible. Thus, the interior structural elements can be included into this entity, forming the legal spaces of the cadastral objects, where the RRRs will be assigned.

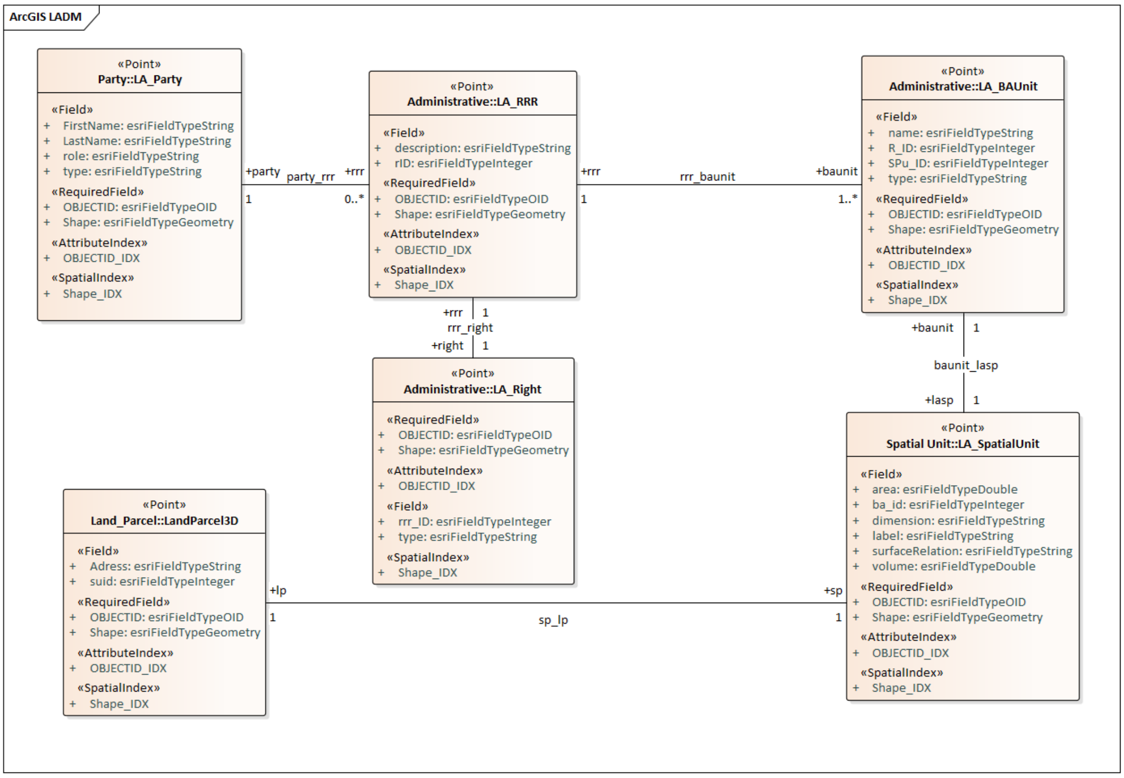


Figure 104. Conceptual DBMS schema of the developed data model, based on the main classes of LADM: LA_Party, LA_RRR, LA_BAUnit and LA_SpatiaUnit

The representation of BIM legal spaces may be achieved utilizing open BIM exchange models, such as the Industry Foundation Class standard (IFC), which is one of the most widely used standard. IfcSpace entity, enables the representation of volumetric (legal) spaces inside a building. With that in mind, a new class named BIM_BuildingUnit3D is created (Figure 105), describing the BIM's cadastral legal spaces. BIM_BuildingUnit3D class is directly linked with BuildingUnit3D class, preserving the necessary information regarding the definition of the volumetric/multipatch geometry of a building unit (property).

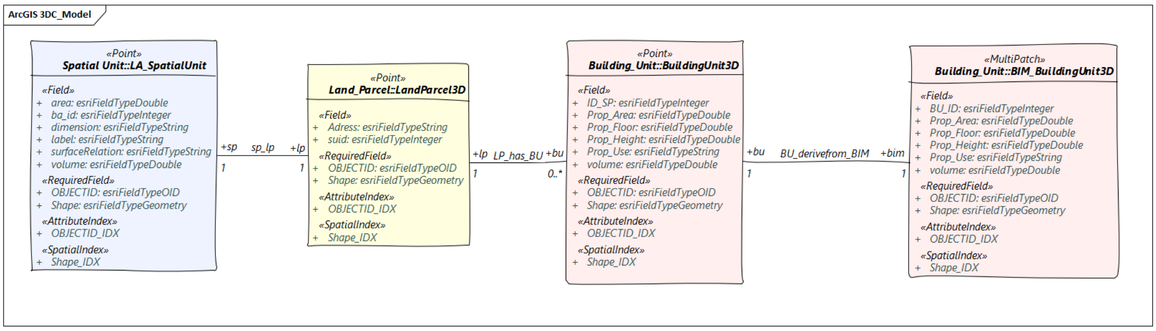


Figure 105. Conceptual DBMS schema of the developed data model, describing the new classes of Land_Parcel, BuildingUnit3D and BIM_BuildingUnit3D; the relationships between them, as well as with the LA_SpatiaUnit class of LADM

6.4.4 Hybrid DBMS Schema

In the fourth stage of the DBMS's development, the generated conceptual schema is modified so as to integrate both of the 3D geometrical representations that investigated in the context of this doctoral dissertation. The BuildingUnit3D class functions as the receptacle of all the potential geometries representing the building units, either with the form of a set of polygonal features or with the form of multipatch features – if BIM data are available (Figure 106). A new class named CustomBuildingUnit3D is created, in order to include the 3D polygonal structures of buildings units. Thus, based on the assumption that a real 3D cadastral object may be defined by one closed polyhedron refined by a set of connected faces, the structure of the 3D polygonal objects included in CustomBuildingUnit3D is created (Figure 107).

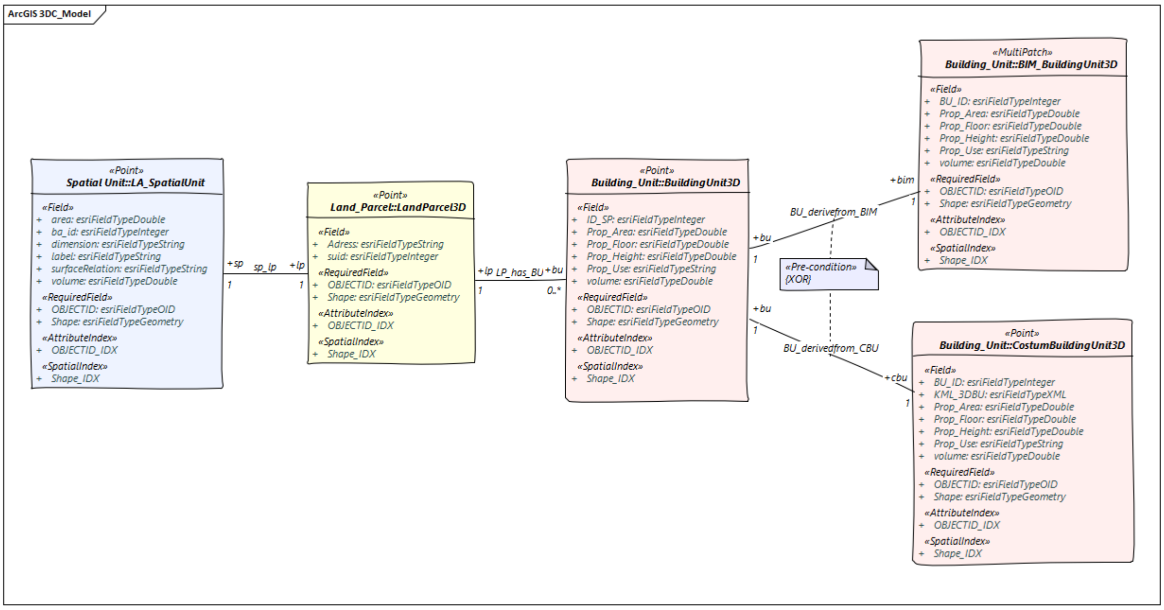


Figure 106. Conceptual DBMS schema of the developed hybrid data model, including both of the potential data structures for buildings units: (i) the 3D polygonal data structure, through the CustomBuildingUnit3D class and (ii) the BIM data – if available – through the BIM_BuildingUnit3D class; as well as the relationships between them.

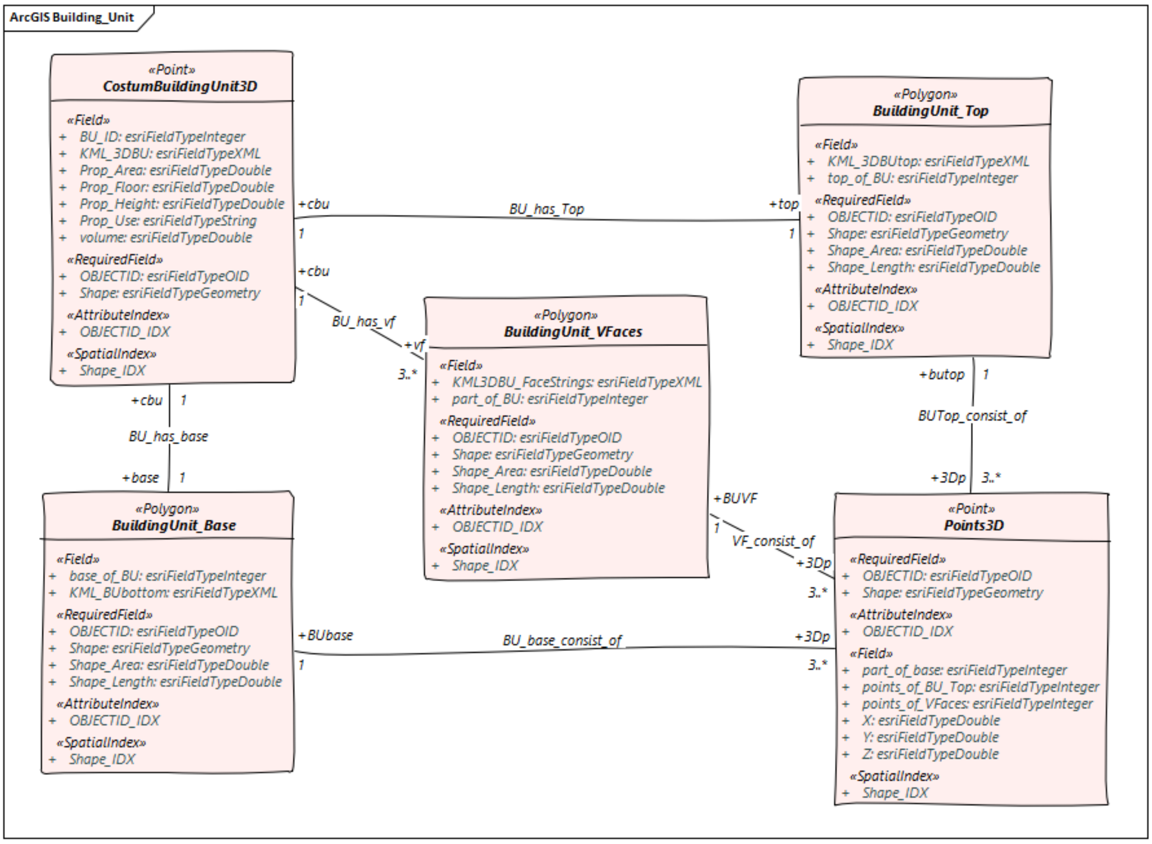


Figure 107. Conceptual schema defining the structure of a 3D polygonal building units.

6.5 Conclusions

In this Chapter, a crowdsourcing-oriented technical system has been presented with the aim of providing an alternative solution to support the initial implementation of 3D cadastral surveys. The developed technical framework adopts the current scientific initiatives, modern technologies, low-cost IT tools, m-services, web services, database management system (DBMS) services and open-sourced software, in the effort to construct its individual technical parts. Its development is based on the simplification, acceleration and cost-reduction of the 3D cadastral surveys procedure. The main contribution of the system concerns the initial acquisition, registration, management, storage, maintenance and updatance of a large amount of 3D crowdsourced cadastral data.

The technical system consists of two interconnected subsystems: the client-side and the server-side. The first concerns the data acquisition toolkit, through which the user may contribute to the process. The second concerns the DBMS which identifies and ensures the precise structuring of the collected data. The main condition that must apply for their communication is the existence of a network connection. Both systems support processes and operations that allow them to tolerate and manage different data types, and more specifically geometric and parametric structures, such as points, lines, planes, surfaces, volumetric objects and BIMs.

For the client-side an open-sourced prototype for Android mobile devices and an open-sourced web application have been developed. The interest of this doctoral dissertation is mainly focused on the use of low-cost mobile devices and consequently on the cadastral mobile application. The development of the web application is carried out in the context of the investigation of potential alternative interfaces. In the already limited range of existing cadastral applications, the developed mobile application is the first attempt to adopt and combine 3D modelling methods and crowdsourcing techniques in this field.

The interface of the developed mobile application is appropriately configured in order to lead and simplify the registration procedure, enabling the active participation of the right holders or other non-professionals. The application can be installed on mobile devices with Android operating system while it is automatically adjusted to varying screen sizes. The main functionalities that are provided through the developed mobile application are summarized in the following.

- Exploits the GPS of the mobile device and provide location information both quantitatively and graphically.
- Browses both cartographic and BIM data. In case of BIM data, the user can view its physical (LoD3) or the legal cadastral spaces (LoD1) through selecting the desired viewing mode. The selection or switch between them is achieved through the selector basemap tool.
- Allows the user to proceed with the cadastral registration utilizing either cartographic or BIM/IFC data – when available.
- Through the "ADD INFORMATION" tool the user may enter all the required cadastral information. The structure of the information form is based on the LADM specifications.
- Provides the user with identification, digitization and selection tools allowing the acquisition of 2D and 3D geometric information, utilizing the available 2D or/and 3D geospatial data. For adverse cases of weak basemap availability, the application also provides additional geometric tools able to assist the registration procedure.
- Enables the automatic generation of 3D land parcel and property unit models as block models (LoD1), using Model-driven approach – when needed. Also, provides the corresponding KML objects of the registered objects.
- Identifies and generates the relationships between the acquired data, and stores them within a 3D LADM-based cadastral geodatabase, located in the server of ArcGIS Online.
- Allows the visualization of the registered 3D cadastral objects in real-time on the mobile phone's screen, both above and below the ground surface, through the visualization tools.

Unlike the developed mobile application, the web application has different functionalities that focus exclusively on the manipulation and registration of BIM data. The main operations that are supported by developed web application are summarized in the following.

- Enables the user to navigate through the 3D scene and view the buildings physical or legal spaces by enabling and/or disabling the corresponding layer that represent the buildings in LoD1 or LoD3. This action is achieved through the layer management tool.
- Provides a 3D measurement tools and a building slicing tool.
- Allows the selection of the property unit through clicking it on the BIM. The selected property unit is highlighted enabling the user to observe and alter his/her choice in case of wrong choice.
- Provides an editor tool enabling the user to insert new or update the current cadastral information into a cadastral LADM-based database located in the Server of ArcGIS Online.

For the server-side a database schema following the specification of the LADM standard has been developed. The utilization of an international standard enhances the adaptability and interoperability of the developed system; while enables the communication between different organizations and parties, worldwide. The structure of the developed database schema includes the main classes of LADM which contain mainly descriptive content; while new spatial classes are generated to support the different geometries of the 3D spatial units, that are provided through the applications.

As LADM does not prescribe the acceptable 3D geometries and representations for the 3D cadastral objects, their determination is based on assumptions supported by several members of the scientific community. Based on the fact that *a valid 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*, the geometries examined in the context of this doctoral dissertation are determined. Thus, the developed database is called to deal with three (3) separate volumetric geometries:

- A closed polyhedron composed by a set of vertices, edges, faces and incidence relationships between them.
- An open polyhedron composed by a set of vertices, edges, faces and incidence relationships between them. The peculiarity of this geometry is that it is mainly translucent toward the 3rd dimension – without an upper or lower limit.
- A closed polyhedron consisting a closed multi-patch surface.

The first two geometries concern the volumetric representation of the property unit and the land parcel, respectively. In this case it is considered that the physical and the legal spaces are identical, as the 3D models do not include any information representing the physical form of each cadastral object.

On the contrary, BIMs provide a rich data source from which various information can be drawn on both the geometry of the physical and legal spaces. In the context of this dissertation only the potential linkage between the LADM and the legal spaces defined in the BIM, has been investigated. This connection is implemented through generating a new spatial class and linking it with the IfcSpace entity. This new class is represented through the third category of the abovementioned geometries. It is worth noting that it is possible to develop a more detailed connection between the LADM and the IFC standard, including not only the legal spaces but also the structural parts presented by the BIM. However, this is outside the scope of this doctoral dissertation.

Chapter 7

Experimental Practices

In this Chapter the potentials of the developed 3D crowdsourced technical framework are further investigated on a practical level. The research plan follows different methodological steps, considering the available geospatial infrastructure of each country, recruiting citizens with or without a certain level of technical skills and tests individual approaches utilizing modern means and tools for capturing 3D cadastral data. During the test stage of this research, the perspectives, effectiveness, usability, reliability and quality of the developed technical framework are investigated.

The practical experiments explore the utilization of both m-services and web-services, emphasizing the usage of mobile applications. The case studies follow the development stages of both the mobile and web applications, including different capabilities and functionalities based on their evolution stage. Each practical application takes advantage of the use of different types of basemaps and tools, in order to cover as many individual cases of data availability as possible. Through the integration of LADM standard, the collected data are formed, providing a more unified and solid data structure. The test areas are mainly concern densely populated urban areas, including also areas with sparse constructions.

First, the pre-processing methodologies applied to the geospatial instances that may form the registration background, is described. In the next Sections, the practical experiments implemented through the developed application for mobile devices, and then the practical experiments carried out through the developed web application, are presented and evaluated. Finally, the main conclusion regarding both the mobile-based and the web-based approach, are realized.

7.1 Technical and IT data preparation

The exploitation of the available 2D and 3D geospatial data in the developed technical framework, presupposes the implementation of several pre-processing steps, ensuring their further utilization and manipulation from the developed crowdsourced cadastral applications. Depending on their 2D or 3D form, a different approach is followed, utilizing either the (i) Cartographic pre-processing methodology, or the (ii) BIM pre-processing methodology.

7.1.1 Cartographic pre-processing methodology

As the technical part of this application has been implemented utilizing the ArcGIS platform for the management of the data, specific processing steps have to be performed. In order the available cartographic data to be used for a GIS implementation, they should be georeferenced. Otherwise, their georeference is made through the environment of ArcGIS Pro. First, the 2D cartographic data are scanned – if it is necessary – in order to be in a digital form, and then they are inserted in ArcGIS Pro software. Through a polynomial transformation the raster datasets are shifted, from the existing location to the spatially correct location, by utilizing visible point features with known coordinates in the Greek national coordinate system (GGRS87 / Greek Grid), 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 world-wide spatial data. Once the basemaps are inserted in ArcGIS Online platform, they may be pulled by the developed applications, if there is internet connection available. The developed applications are 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 Figure 108.

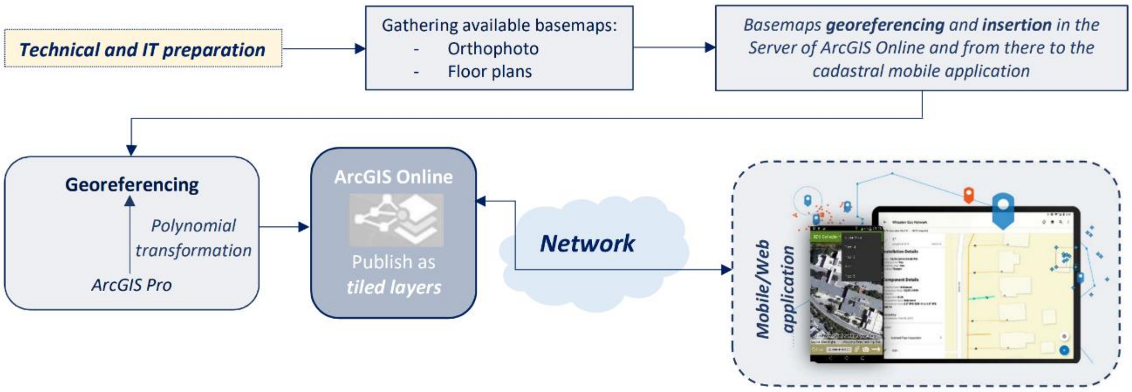


Figure 108. Technical and IT data preparation – Overview of the Cartographic pre-processing methodology.

7.1.2 BIM pre-processing methodology

For the exploitation of BIM data from the developed applications, different pre-processing steps were followed. In this doctoral dissertation, both the use of existing BIM and the generation of new BIM, aiming to have a clear insight about the structure elements required for 3D crowdsourced cadastral surveys, were investigated. The pre-existed or new BIM models used in this research, were generated through the Autodesk Revit software, utilizing the available georeferenced floor plans of the building/construction. Furthermore, as for cartographic pre-processing methodology, so in BIM pre-processing methodology, the ArcGIS Pro software and the platform of ArcGIS Online were utilized, aiming to establish the necessary connection between the data and the developed applications.

The (re-)use of already existed BIM data, requires its availability in IFC format, enabling the translation of BIM's 3D spatial information into the ArcGIS Pro platform and therefore to ArcGIS Online (Figure 109). In the first step, the IFC model was imported into the ArcGIS Pro environment, enabling the further manipulation of the BIM for GIS/cadastral purposes. ArcGIS Pro's quick import tool from the Data Interoperability Toolbox was utilized in order to import the generated IFC model into an ArcGIS file geodatabase, making the BIM's spaces available for loading into the project. The generated geodatabase refers to the Greek Grid (ESPG: 2100) Projected Coordinate Reference System (PCRS), which in the experiments of this research is the PCRS of the BIM. However, the 3D scene of ArcGIS Pro refers to WGS84, which is the Geographic Coordinate Reference System (GCRS). Thus, the generated database had to be converted to WGS84 utilizing the Batch Project tool of ArcGIS Pro.

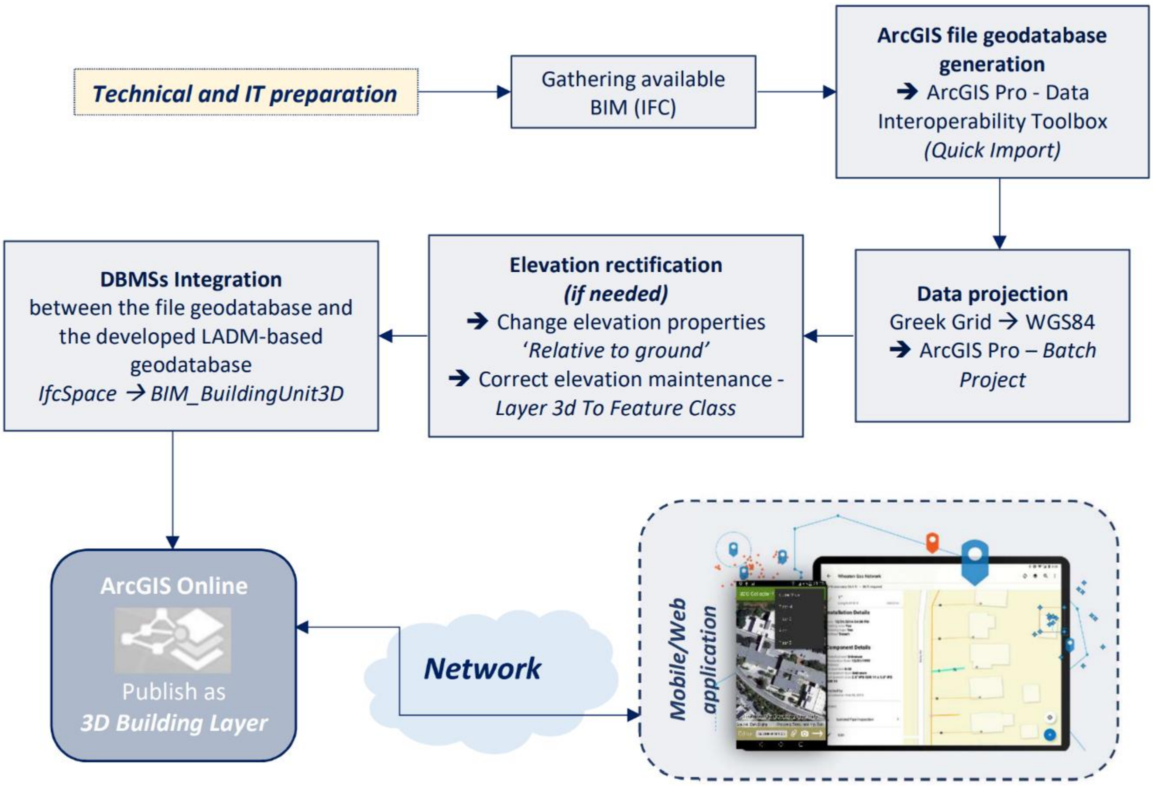


Figure 109. Technical and IT data preparation – Overview of the BIM pre-processing methodology.

Although the coordinates of the "survey point" and the orientation of the BIM through the identification of the "true North" were defined in Revit, the examined IFC models were not correctly positioned in 3D space. In the context of BIM–GIS integration, geo-referencing BIM models can be problematic and constitutes a major issue in practice. For these particular studies, the IFC2x3 version was utilized. Although this version embeds spatial reference information, mismatches may occur when importing the model to a GIS environment (Zhu & Wu, 2021). However, this problem may be solved in the IFC4 version by introducing a new entity that includes and maintains all the necessary elements for the georeference of the model. The IFC4 version is newly emerging but may be utilized and tested for future research in this field.

The models were horizontally aligned close to their correct position with an average offset of 18 cm, while their vertical alignment was incorrect, when the building's surface altitudes were not defined during the generation of BIM through Revit. With undeclared orthometric heights in BIM, considering the ground floor as the beginning of measuring heights (+0), the BIM appears to be submerged in the ground, during its visualization through ArcGIS Pro. To overcome this problem, the models were moved to their correct horizontal position utilizing the editing tools of ArcGIS Pro. Subsequently, the elevation of the features of each generated feature class was set to "Relative to ground" in order for the features to appear at their correct height. Subsequently, new feature classes with the correct elevation were created utilizing the "Layer 3d To Feature Class" tool. It is noted that although the final model appears in its correct position horizontally, some ambiguities regarding its vertical alignment remain. This is mainly due to the used DTM from ESRI, which refers to a global basis and thus include some inaccuracies. However, this problem can be solved by using a more up-to-date and accurate DTM. Nevertheless, the final results were satisfactory for the purpose of this research. In the last step, once the correct geodatabase was generated for each BIM, the IfcSpace entity was connected to the BIM_BuildingUnit3Dclass of the developed LADM-based geodatabase, which was enriched with the necessary geometric information concerning the cadastral legal spaces. Subsequently, the georeferenced BIMs are published in ArcGIS Online as Scene Layer. Once the BIMs were inserted in ArcGIS Online platform, they could be pulled by the developed applications, if there is internet connection available.

Besides the utilization of already existed BIMs, the creation of a new BIM for the new building, was conducted through Revit software. In the first step, the physical spaces were created in LoD3, describing the real characteristics of the buildings in detail. Then, the legal spaces were created utilizing the Area and Schedule function of Revit, enabling the identification of the 2D boundaries of each 3D legal space and the insertion of the necessary semantic information concerning the property's RRRs, respectively. Finally, the created 2D spaces were matched with the IfcSpace entity in the exported IFC model, providing the 3D legal spaces. Then the previously described procedure was followed, for inserting the IFC into ArcGIS Pro and therefore to the ArcGIS Online platform (Figure 109). It is noted that the identification of the different types of legal objects is outside of the scope of this study. The management and definition of the different types of the legal spaces and the proper placement of the legal boundaries (e.g., the middle of the wall) remain under investigation. In the following implementations, the legal spaces are assumed to be either correctly defined or defined under certain assumptions, focusing more on the evaluation and assessment of the proposed technical framework regarding the submission of the cadastral information by the citizens/rights holders.

7.2 Mobile-based Practical Implementations

In this Section, eight (8) experimental implementations performed in distinct urban areas of Greece, are presented. Each implementation utilizes different geospatial background and tools, leading to individual accuracy levels of the final outcome. According to these diversifications, the case studies are grouped into four (4) discrete approaches:

(i) The Cartographic-oriented approach, with the utilization of an orthophoto overlaid with architectural floor plans, as registration basemap.
(ii) The Geometric-oriented approach, with the combined utilization of an orthophoto basemap and geometric tools, assisting the identification procedure.
(iii) The BIM-oriented approach, with the utilization of BIM data – when they are available – as registration background, ensuring high accuracy results.
(iv) The Hybrid approach, constituting a combination of the above.

7.2.1 Cartographic-oriented Approach

Following the cartographic-oriented approach, five (5) case studies were implemented for individual multi-story buildings located at:

(i) the National Technical University of Athens, at the School of Rural, Surveying and Geoinformatics Engineering (SRSG), Zografou, Greece (case studies 1, 3 & 4)
(ii) the city of Larisa, in northern Greece (case study 2),
(iii) the neighborhood of Pagrati, in central Athens, Greece (case study 5).

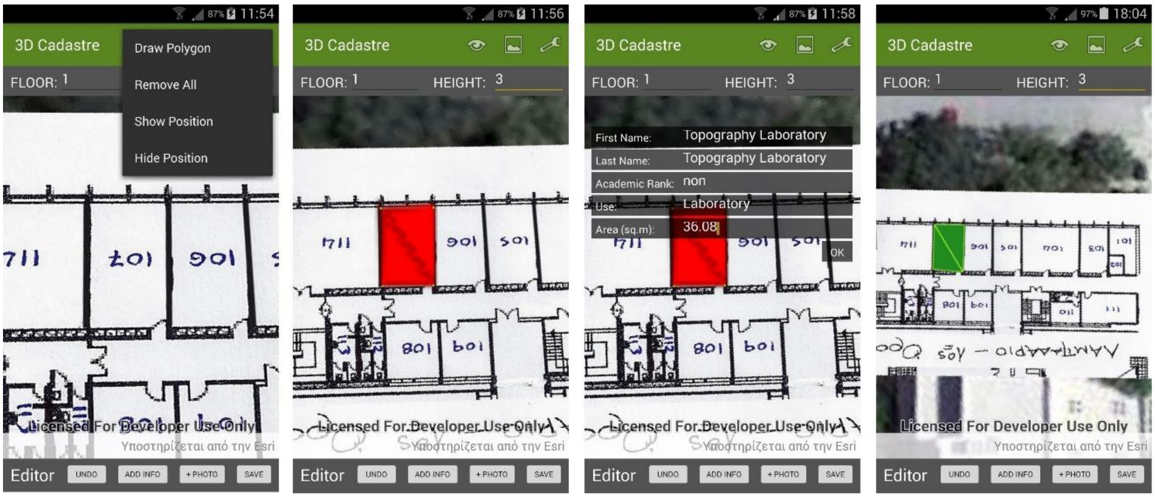
The case studies examine different development stages of the crowdsourced framework, investigating the effect of each technical or methodological restructuring, into the effectiveness of the entire framework.

7.2.1.1 Case study 1

The first practical experiment was implemented for a 2-storey building of the SRSG, NTUA (Figure 110 left). For research purposes, the test was performed in cooperation with the employees, who were assumed as volunteers/right holders. Data collection process was conducted with the assumption that the building may be considered as a block of apartments and each office room is an individual property (e.g., an apartment). The main objective was to identify the boundaries of each office room of the first floor of the building, and record some basic descriptive information. For this particular investigation, the collected data include the polygonal boundary of the room, the height of the room, the floor number and the descriptive information which concerns the room holder (name, academic rank) and the room (use, area).

For the implementation, an orthophoto of the test area at the scale of 1:1000 and a floor plan of the first floor of the academic building at the scale of 1:200, have been used as basemaps (Figure 110 right). In order the volunteers to be oriented regarding their position on the available basemap, the GPS of the mobile device was utilized. While the volunteers were in the interior of building, the positioning accuracy of the GPS was about 1-3 m, and thus it was only used to avoid gross orientation errors and not for the identification of the exact position of each property in 3D space.

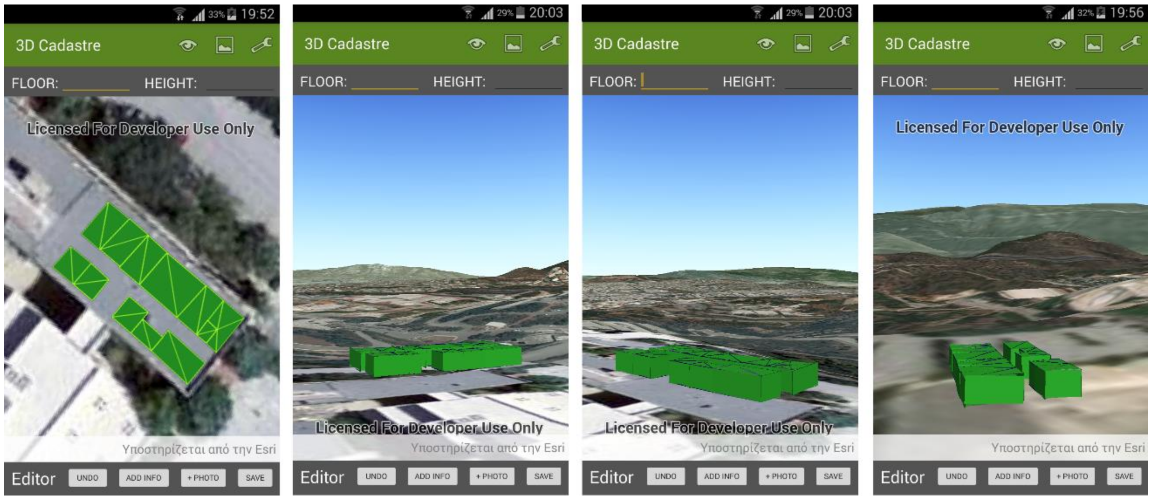
Figure 110. Orthophoto of the test area (in red) at the scale of 1:1000 (left) and a floor plan of the first floor of the academic building at the scale of 1:200 (right).



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

Figure 111. Example of the recording process, including the polygon digitazation and the insertion of the adequate information. (a) Selection of polygon drowing tool. (b) Digitization of the studied property. (c) Selection of ADD INFO tool and insertion of the adequate information. (d) Presentation of the declared property, on the basemap.

Using the mobile application, the registration process was conducted by selecting features (points) on the first floor basemap, that is the first floor's plan, in order to form the surrounding polygon of each room. The insertion of the adequate descriptive information, follows the digitization of each polygon. Utilizing the mobile's application tools, the user was able to alter any wrong input data and update the information he/she has entered into the application. The described procedure is presented in Figure 111. Once the data referring to each room are imported and controlled, the 3D visualization of the registered room was achievable, through the selection of the corresponding tool (Figure 112). As the last step of the registration procedure, the collected data were stored in the Cloud of ArcGIS Online, updating the system with the new records and the corresponding 3D models.



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

Figure 112. 3D Parametric Models of the results, through the visualization tool of the developed mobile application. (a) Vertical view of the scene (via Vertical View tool). (b),(c) and (d) 3D View of the declared properties, through different perspectives (via 3D View tool).

During the registration process, no problem has occurred. The mobile application was easy to use and the necessary information were successfully collected. The availability of the floor plan was helpful as it clearly presents the boundaries of each room. The only detected difficulty was the uncertain selection of the corner points of the digitized polygons, as in the floor plan the boundary of each room was presented as a thick line including the walls width (the walls that separate each office are thin). The overall procedure lasted about less than an hour, as the registration of each room lasted 3-5 minutes. The recording time depends heavily on the complexity of each office shape and the familiarity of the user with mobile application.

Following the completion of the registration procedure, the results were exported by the Cloud of ArcGIS Online and the draft crowdsourced 3D room models were generated (Figure 113). In order to test the crowdsourced data in terms of accuracy and completeness, a comparisson according to the reference data was conducted. As reference data, a diagramm describing the floor plan, was used. As 3D models generated by Model-driven methods, based on the footprint of each room, the comparison should be conducted between the reference data and the digitized polygons. The evaluation of the results shows that there were no significant discrepancies between the compared data (Figure 114). The average accuracy deviation of the two datasets was 0.15 m while their maximum and minimum deviation was approximately 0.36 m and 0.03m, respectively. The quality control reveals that the proposed registration procedure utilizing the self-developed mobile application, had satisfactory results in terms of data accuracy and data visualization. The produced 3D models were properly placed in 3D space, while the small shape defects are caused by the imported errors in the digitization process. The proposed procedure is promising as the results can be greatly improved after the proper training and briefing of volunteers, by a trained volunteer or a professional surveyor.

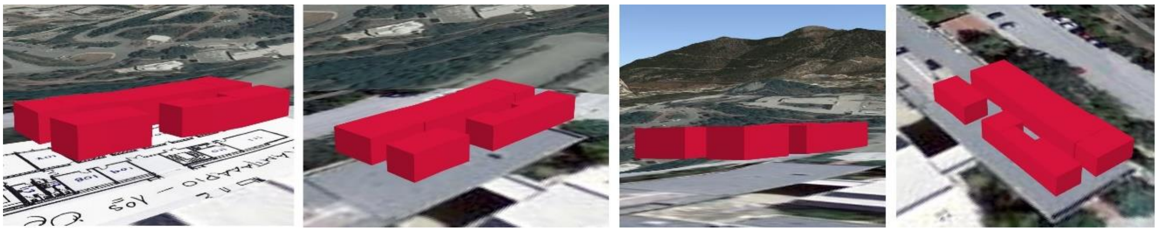


Figure 113. 3D Visualization of the results in ArcGIS Online. Different view of the declared properties, through different perspectives.

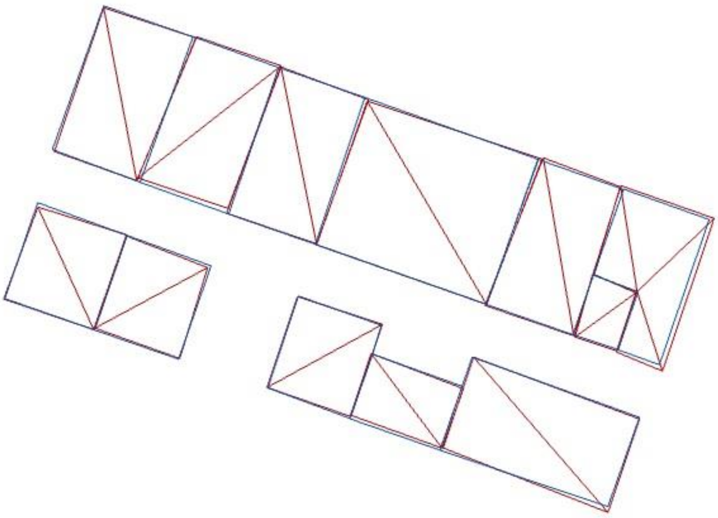


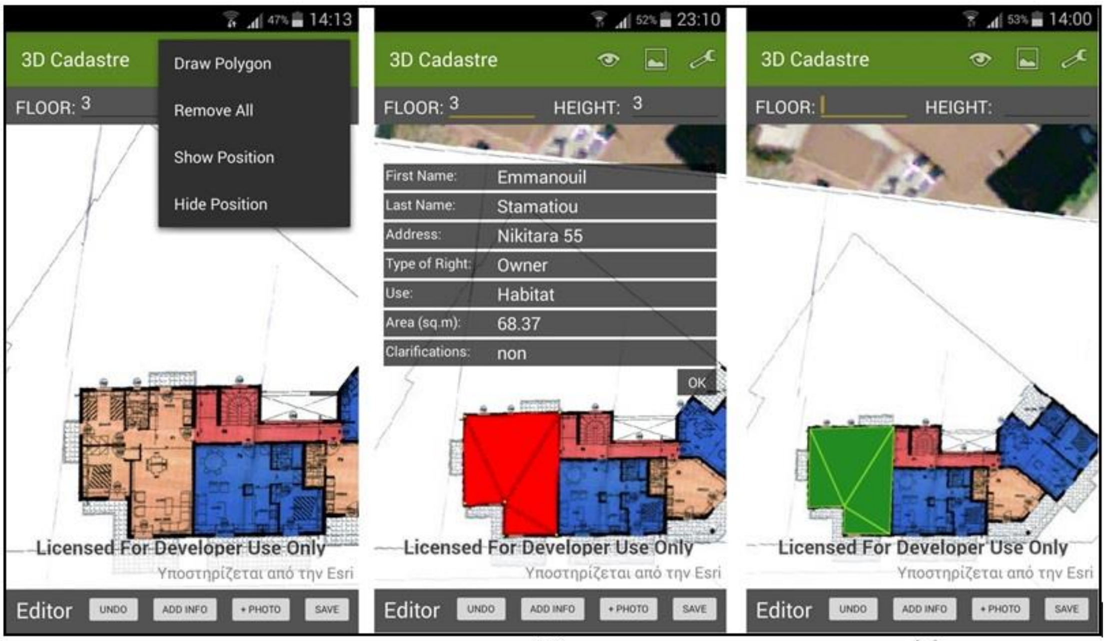
Figure 114. Comparison between the digitized polygons (in red) and the reference data (in blue).

7.2.1.2 Case study 2

In the second practical attempt, a larger scale experiment was implemented trying to manage more complex cases of multidimensional and overlapping property rights, while introducing the crowdsourced process to citizens/right holders without certain level of technical skills. The test area is located in the city of Larisa, in northern Greece. The recording levels include levels above and below the terrain, making both the process and the results quite interesting. The main objective is to identify the boundaries of each property unit together with some basic descriptive information referring to the ownership by the rights holders (as volunteers). The citizens/ holders of rights were middle-aged local people of various levels of education and skills, but well informed as to the use of smart phones. After a brief training about the functionalities of the developed mobile application, they were familiar with the function of the mobile application.

When using the developed mobile cadastral application, the rights holders are asked to digitize the boundaries, declare the height and the floor in which their properties are located, and submit information about the property unit. The basic descriptive information concerns the rights holder’s personal data (first name, last name, type of rights, etc.), information about the property (address, use type, area size) and additional descriptive information about the property unit, which may be declared by the rights holder. For implementation of the proposed procedure, an orthophoto of the case-study area at a scale of 1:1000 and the floor plans of the underground floor, the ground floor, the first and the third floor at a scale of 1:50, are used as basemaps (Figure 115). The GPS positional accuracy is about 1-4 m, and is used only to avoid gross errors during rights holder’s orientation in the test area. To achieve the required geometric accuracy, the digitization is done using the cursor, moving it manually on the basemap.

Figure 115. Orthophoto of the case-study area at the scale of 1:1000 (top left) and the floor plans of the underground floor (top right), the ground floor (bottom left), and third floor (bottom right) at the scale of 1:50.



(a) (b) (c)

Figure 116. Example of the recording process on the mobile application, including (a) the selection of the digitization tool (b) the polygon digitization and insertion of the adequate information and (c) the presentation of the declared property unit on the basemap.

The registration process was started by digitizing the land parcel property boundaries on the basemap. Then the right holder had to identify the property unit boundaries by selecting the floor in which the property unit is located. The selection of the proper basemap was conducted through the selector basemap tool and therefore the selection of features (points) on the basemap, using the digitization tool, in order to form the polygon of the property unit. Next, using the insertion tool, the right holders were inserted the adequate descriptive information regarding the declared rights and the rights holder's personal data. The right holder was able to check and correct any wrong input and update the information. This procedure is presented in Figure 116. Once the data referring to each property unit were imported and checked, the 3D visualization tools allow the user to see the 3D property unit model, above or below the ground, through the selection of the corresponding tool (Figures 117 & 118). In the last step of the registration procedure, the collected data were stored in the ArcGIS Online Cloud, updating the system with the new records and the corresponding 3D property unit models.

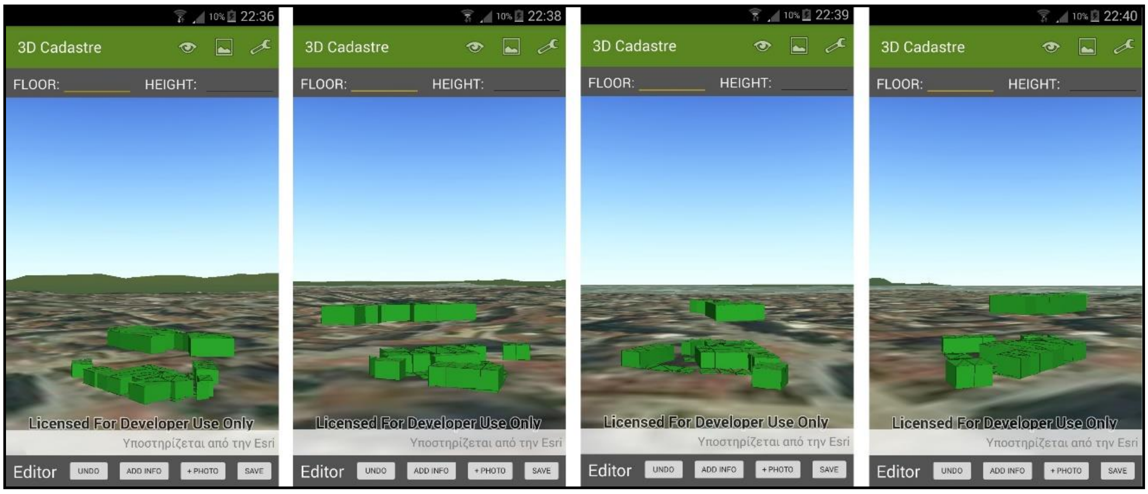


Figure 117. 3D Visualization of the declared properties (in green) in their absolute position on the ground, using the 3D View tool of the mobile application.

Figure 118. 3D Visualization of the declared properties (in green) in their relative position (above and below) with the ground (in red), using the 3D Model tool of the mobile application.

The overall procedure was relatively quick as the registration of each property lasts about 3-7 minutes, based on geometrical characteristics of the boundary and the user's digital skills. No major problems occurred during the data collection through the mobile application; the usage of the mobile application is considered to be easy and understandable by the users. The existence of an architectural floor plan is really helpful, as it clearly presents the boundaries of each room, leading to successful results. However, a particular difficulty has been identified that is worth mentioning. This refers to errors that may be imported during the procedure, due to the quality of the utilized DTM (Digital Terrain Model). Irregularities such as incorrect altitudes of certain points in the DTM may lead to significant errors during the 3D data collection procedure.

Following the completion of the registration procedure by the rights holders, the results are exported from ArcGIS Online, and the draft crowdsourced 3D property unit models are generated (Figures 119 & 120). The data are then evaluated in terms of accuracy, quality and completeness, through a comparison with the reference data. The plans describing each unit on the floor plans are used as reference data (Figure 121). The evaluation of the results shows that there are no significant discrepancies between the two data sets (Figure 121). The average accuracy deviation between the two data sets is 0.17 m while the maximum and minimum deviation is approximately 0.42 m and 0.01 m, respectively. The achieved accuracy is satisfactory, revealing that the proposed registration procedure utilizing the mobile application leads to reliable results. The generation and placement of the 3D property unit models was correct. However, some minor geometric inconsistencies were identified, due to the imported errors while selecting points on screen as well as the incorrect altitude values that the DTM used may include.

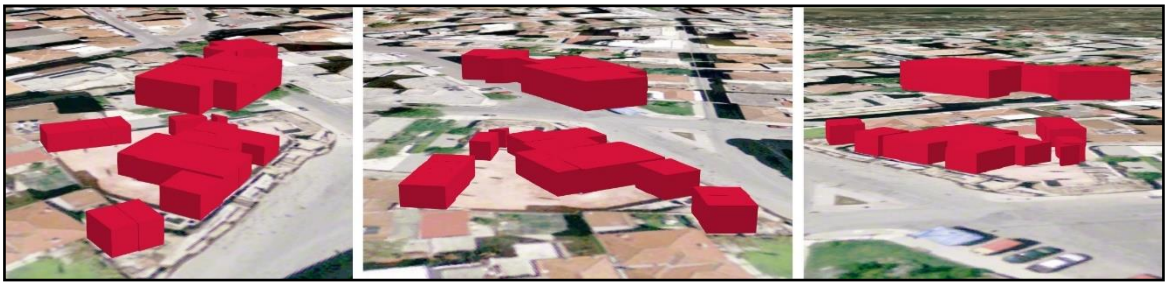


Figure 119. Visualization of 3D property unit models (in red) in their absolute position on the ground, as they are generated in the ArcGIS Online.

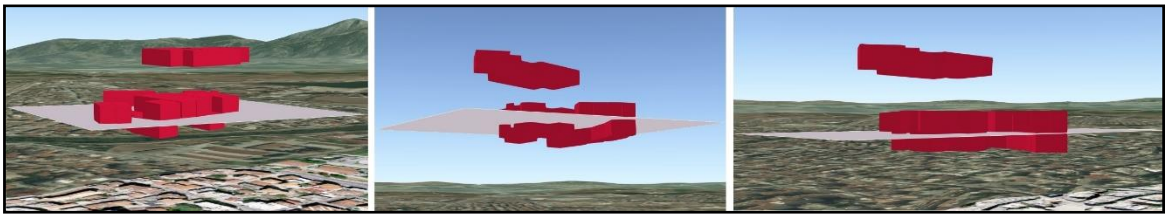


Figure 120. Visualization of 3D property unit models (in red) in their relative position (above and below) with the ground (in violet), as they are generated in ArcGIS Online.

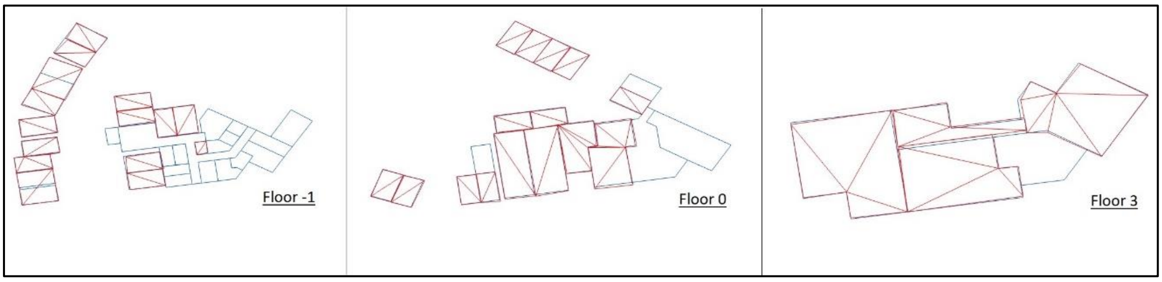


Figure 121. Comparison between the digitized polygons (in red) and the reference data (in blue), for each one of the studied building floors.

7.2.1.3 Case study 3

Having examined the potentialities of the technical framework regarding the 3D modeling and visualization of the property units, as well as the collection of 2D and 3D geometric and descriptive data, the research proceeds with the integration of LADM standard as the main data model for structuring the cadastral information. Thus, in the third practical experiment the upgraded version of the technical framework, with an optimized user interface that leads the registration procedure, was investigated.

The developed framework was tested for the multi-storey building of the SRSG, NTUA for which the first practical experiment had been performed, retaining the assumption that the building is considered as a block of apartments and each office room as an individual property unit. In contrary with the first experiment, all the floors of the building were studied, including the levels above and below the ground surface. Furthermore, the type of the collected cadastral data was differentiated, as it was adapted to LADM specifications. For this case study the collected data include the building- and each room-outline coordinates, 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 (floor, height, use, area size, volume). As parcel boundaries, the boundaries of the NTUA campus parcel were selected.

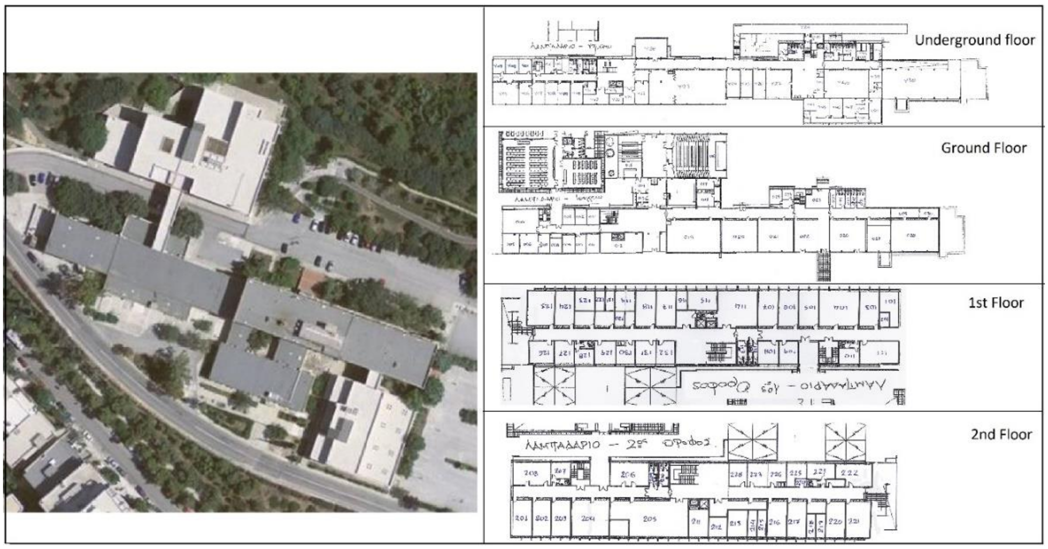


Figure 122. Orthophoto of the case-study area at the scale of 1:1000 (left) and the floor plans of the underground floor (top right), the ground floor (2nd row right from the top), first floor (3nd row right from the top) and second floor (bottom row right).

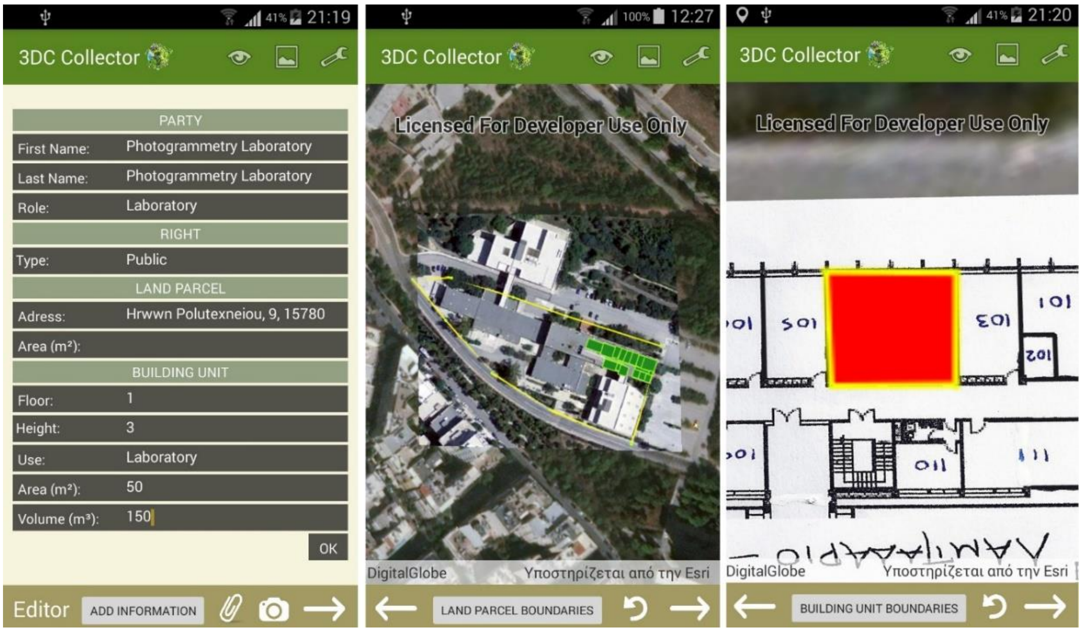


Figure 123. Example of the recording process through the developed mobile application, including (a) the insertion of the adequate cadastral information, (b) the polygon digitization on the parcel basemap describing the land parcel and (c) the polygon digitization on the floor basemap describing the building unit, on the basemap.

For the test implementation, an orthophoto of the test area at a scale of 1:1000 and the floor plans of the underground floor, the ground floor, the first and the second floor at a scale of 1:200, were used as basemaps (Figure 122). Data collection was performed in cooperation with the employees, who were assumed as rights holders. After a training session aiming to enlighten volunteers regarding the usage of the mobile application, the registration process was begun.

During the first phase of the cadastral procedure, the insertion of the adequate descriptive information regarding the declared of rights and the right holder's data, was conducted. Verification images and legal documents (in an official procedure) may be inserted, in order to support the registration procedure. Next, the identification of the land parcel boundaries and the boundaries of each property unit, was conducted by selecting the appropriate basemap (orthophoto or floor plan) and tapping the adequate boundary points on screen, utilizing the digitization tool. The described procedure is presented in Figure 123.

The 3D property unit models were successfully generated through the mobile application (Figure 124) and the collected data were stored in the developed LADM-based database in the Cloud of ArcGIS Online. The updated version of the mobile application was easy to use while the overall procedure was relatively quick as the registration of each property lasts about 5-7 minutes. The existence of the architectural plans was proved again to be very helpful, as the building unit-boundaries are distinct, increasing the geometric accuracy of the final results. After the completion of the registration procedure, the LADM-based database was exported from the Cloud of ArcGIS Online, in order to be evaluated. The results showed that the average accuracy deviation between the compared datasets was 0.17 m while their maximum and minimum deviation is approximately 0.49 m and 0.03 m, respectively (Figure 125).

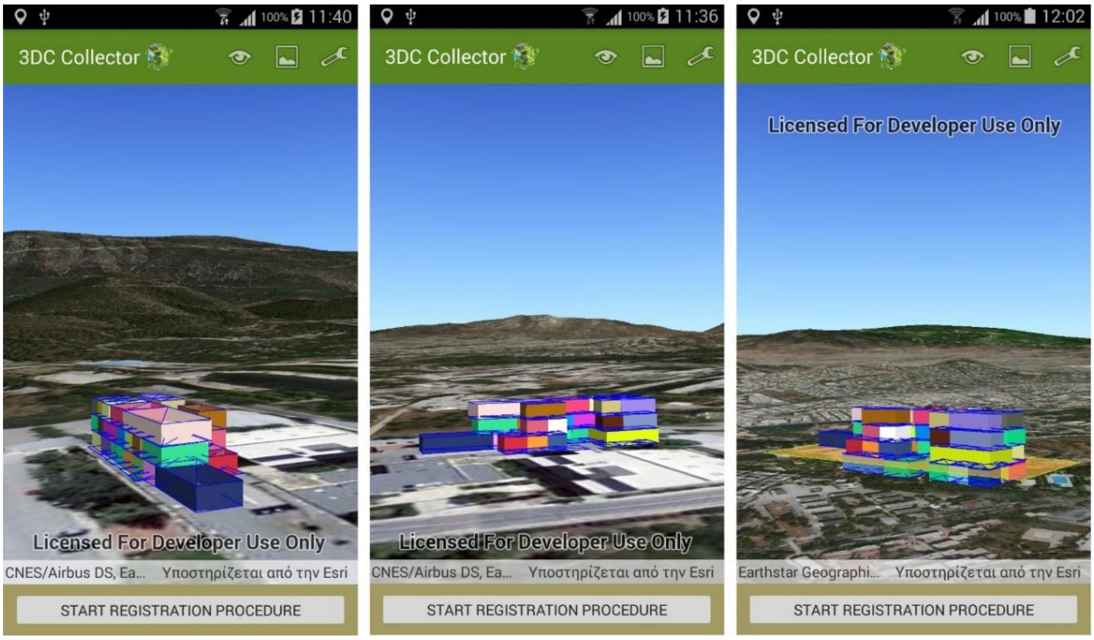


Figure 124. 3D models of the declared properties above (left, middle) as well as above and below (right) the ground surface, using the 3D Model tool of the developed mobile application.

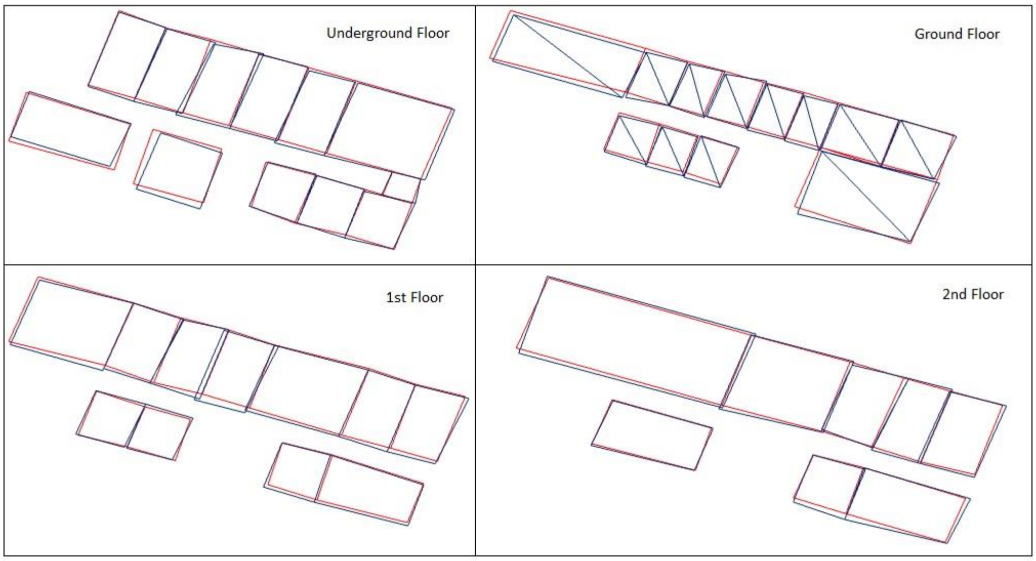


Figure 125. Comparison between the digitized polygons (in blue) and the reference data (in red), for each one of the studied building floors.

7.2.1.4 Case study 4

Remaining in the same study area and expanding the number of the property units to be registered, the fourth practical experiment was implemented. The volunteers' sample was differentiated, as in addition to employees, students were also recruited to perform the 3D cadastral registration. The main objective of this case study as well as the type of the collected data, are similar with the third practical experiment, except that in this case study the potentials of the fourth phase of the developed crowdsourced methodology, was further explored. One of the most important phases for the commencement of the registration procedure is the technical and IT preparation, by the team leader. Thus, in this practical experiment the volunteers were assumed as team leaders, in order to proceed the collection and management of the existing architectural plans as well as for their preparation and insertion in the mobile application.

As basemaps, an orthophoto of the test area at a scale of 1:1000 (Figure 126) and the floor plans of the underground floor, the ground floor, the first and the second floor of each one of the two building, at a scale of 1:200 (Figure 127), were utilized. The volunteers, were young adult people with advanced digital skills (engineering or technical skills) as they were students from various NTUA Schools and/or young surveyors, and they were well informed about the use of smart phones. After a brief training, concerning the objectives of this project, the training of the volunteers was begun. The volunteers were trained from our research team regarding the necessary technical and IT preparation which data had to pass through, in order to be in an exploitable form to be utilized by the mobile application, as well as for the functionalities of the developed mobile application. Of course, during this process there were some difficulties regarding the usage of the utilized software and the online platform. However, through proper training and support materials (tutorials, videos etc.), these drawbacks can be resolved.

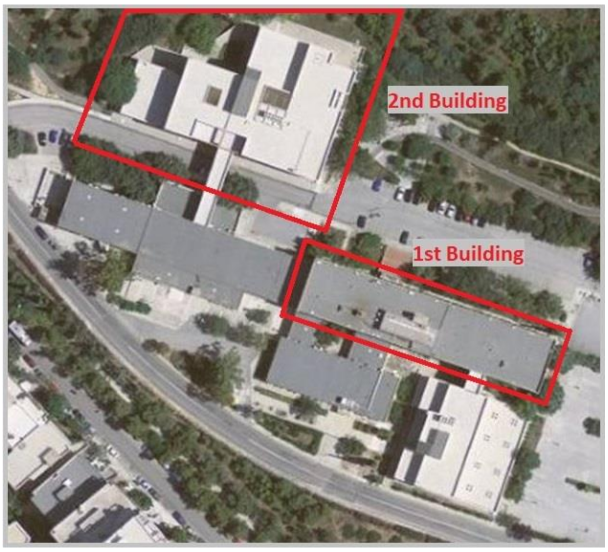


Figure 126. Orthophoto of the test area at the scale of 1:1000, depicting the studied buildings.

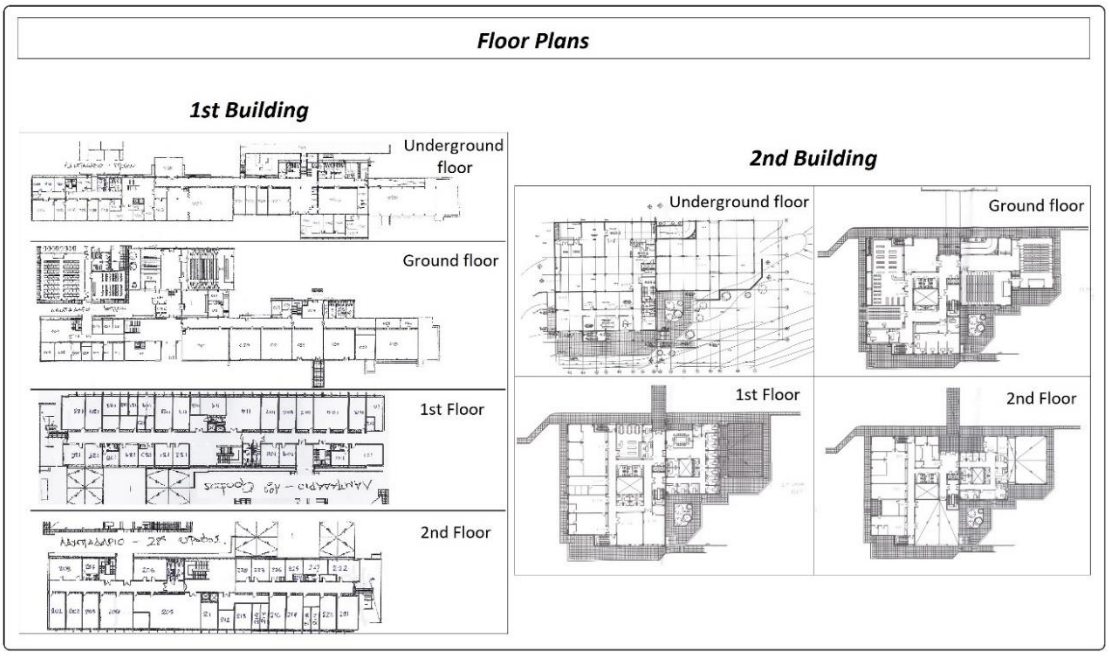


Figure 127. Floor plans of the underground floor, the ground floor, first floor and second floor of the 1st (left) and the 2nd (right) building, at the scale of 1:200.

Following the sequence of the registration steps, the volunteers were able to start and complete succesfully the registration procedure of both buildings, through the mobile application. During the whole procedure a member of the research team was at the volunteers' disposal in order to resolve any questions that they may had. Figure 128 (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 Figure 129, the described registration procedure, is presented.

Figure 128. Group of volunteers in cooperation with the team leader, during the registration of a meeting room of the School of Rural, Surveying and Geoinformatics Engineering, NTUA.

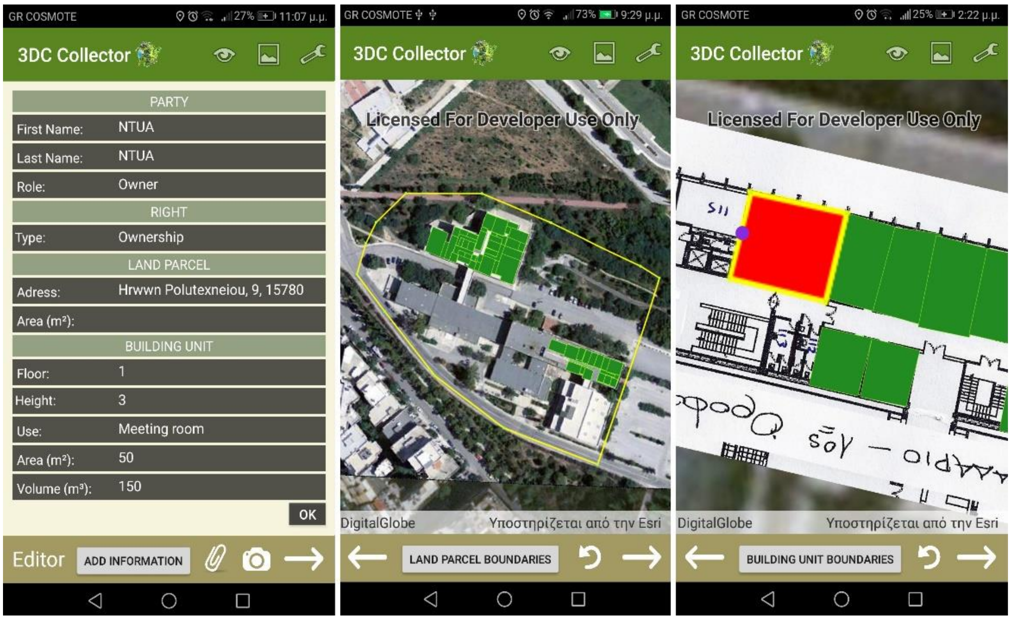


Figure 129. Example of the recording process through the developed mobile application, including (left) the insertion of the adequate information, (middle) the polygon digitization describing the land parcel and (right) the polygon digitization describing the building unit, on the basemap.

The registration procedure was completed without any major problem, as the necessary information were collected through the mobile application. The 3D models of the declared rooms were visualized through the selection of the 3D model tool (Figure 130). The registration of each property lasted about 10-12 minutes (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 practical experiment, 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 achieved.

Figure 130. 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.

Once the overall procedure was 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 (Figure 131). For the evaluation of the results, a comparison with the reference data was conducted. The results were acceptable, as no significant discrepancies between the compared data were detected. The average accuracy deviation between them was about 0.21m and their maximum and minimum deviation was approximately 0.75 m and 0.03 m, respectively (Figure 132). 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.

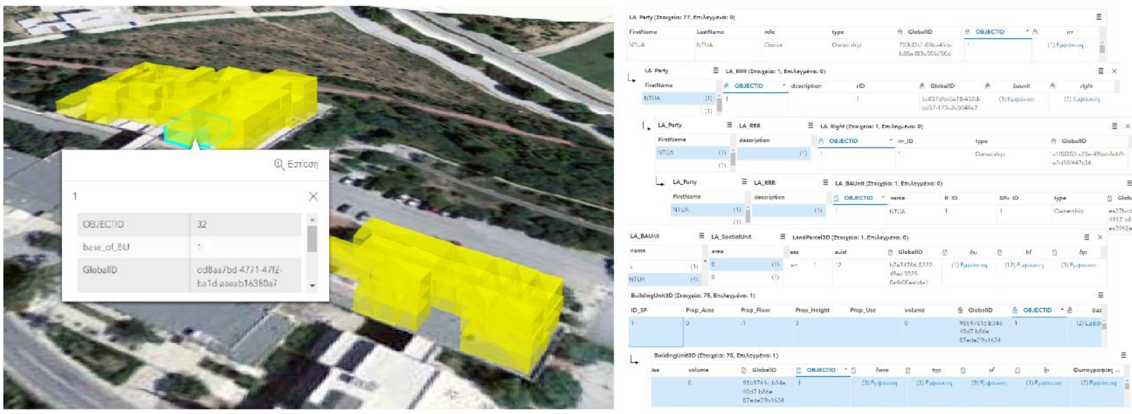


Figure 131. Visualization of the generated crowdsourced 3D building unit model in ArcGIS Online. Inspection of crowdsourced cadastral information either by selecting the 3D building unit model (left), or by accessing the DBMS in ArcGIS Online (right).

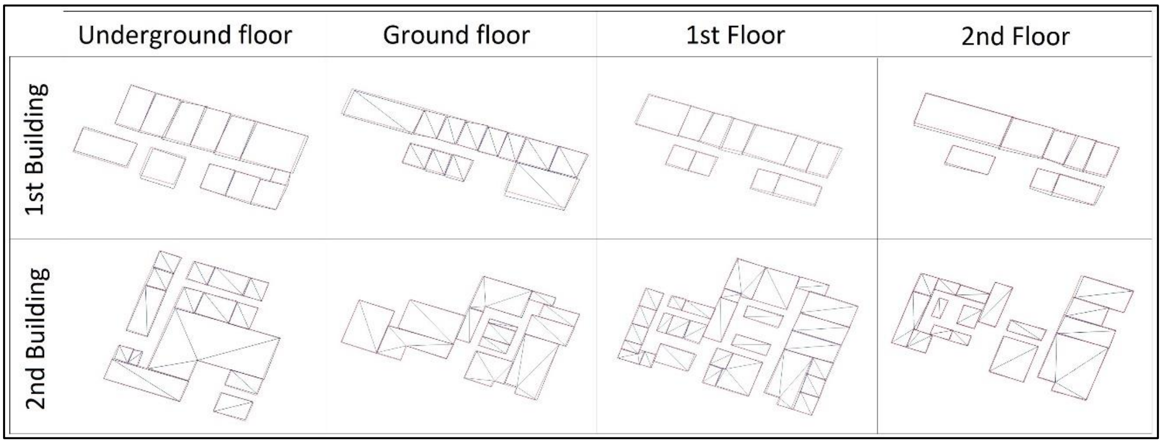


Figure 132. Comparison between the digitized polygons (in blue) and the reference data (in red), for each one of the studied building floors.

7.2.1.5 Case study 5

The fifth practical experiment re-examines the upgraded version of the crowdsourced framework, in real surveying circumstances, recruiting a group of volunteers with varying ages, educational level and digital skills. For the test implementation, a multi-storey building, located in the urban area of Pagrati, in the center of Athens, was utilized. The studied building is characterized by multiple and overlapping property rights, as well as by properties with complex geometries. The main objective was to identify the polygonal boundaries of each property unit together with some basic descriptive information referring to the ownership.

The practical experiment consisted of four (4) discrete stages: (i) the initial data gathering, (ii) the volunteers training, (iii) the field work, (iv) the extraction and evaluation of the results. At the first stage, the collection of the existing geospatial information (aerial photos, orthophotos, architectural plans, etc.), was accomplished. An orthophoto of the test area at a scale of 1:1000 (Figure 133) and the floor plans of the two underground floors, the ground floor and the rest seven (7) floors above the ground, at a scale of 1:100, were utilized as basemaps (Figure 134). For this test, the collected data include the land parcels and the property/building unit boundaries, the height of each property, the floor number and the descriptive information about the building (area code, address), the rights holder (name, role, type of rights) and the property geometric data (floor, height, use, area size, volume).

In the second stage, the group of the volunteers was gathered, trained and organized. The volunteers were middle-aged citizens of various levels of education and skills and well enough updated as to the use of smart phones (Figure 135). At first, the volunteers were informed about the main objectives of this project. and trained regarding the necessary technical preparation of the collected data and the functionalities of the developed mobile application. Next, the mobile application was installed in their smart phones, and after a brief discussion with our scientific coordinator about any technical issue or question, the volunteers were familiarized with the mobile application, and so the registration procedure was started. Figure 136 presents a group of volunteers during the training session.

Figure 133. Orthophoto of the case-study area at the scale of 1:1000.

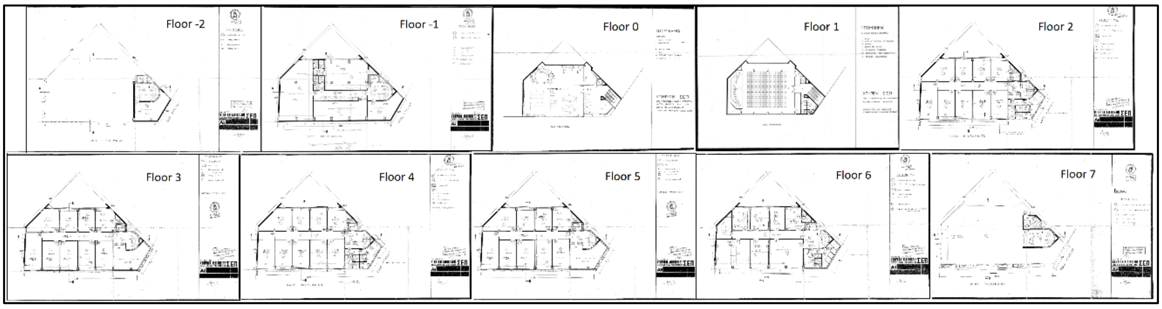


Figure 134. The floor plans of the two underground floors, the ground floor, and the rest seven (7) floors above the ground, at a scale of 1:100.

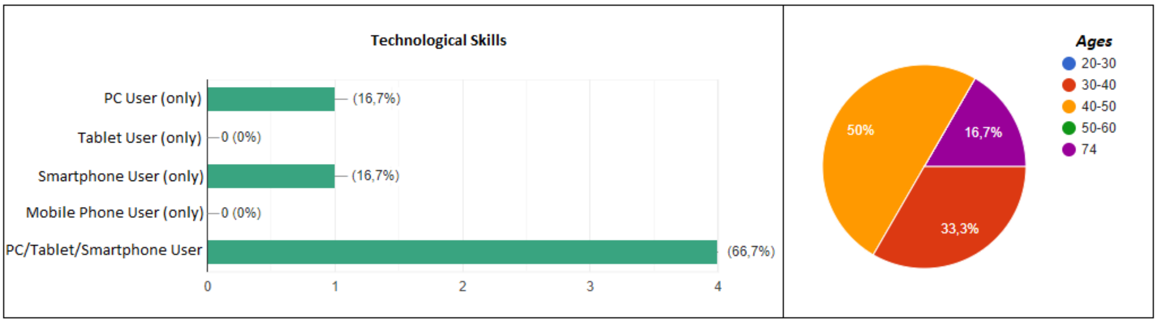


Figure 135. The technological skills (left), and the age distribution of the volunteers (right).

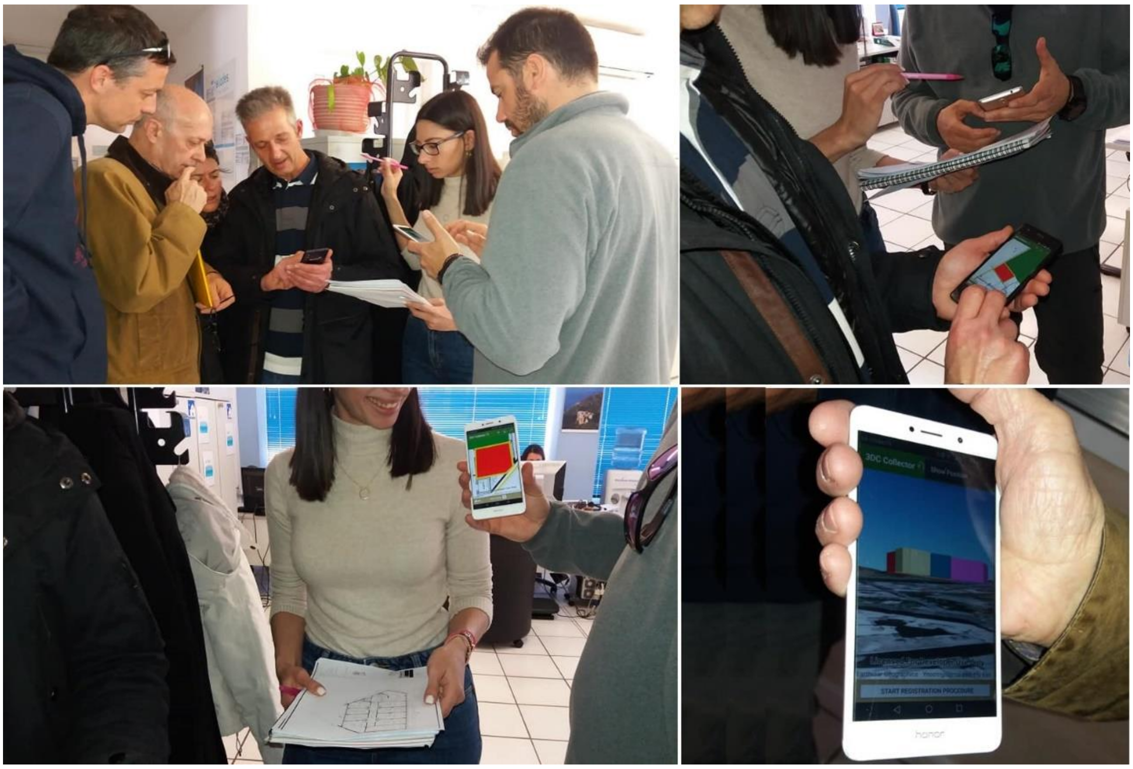


Figure 136. Group of volunteers in cooperation with the scientific coordinator, during the training session.

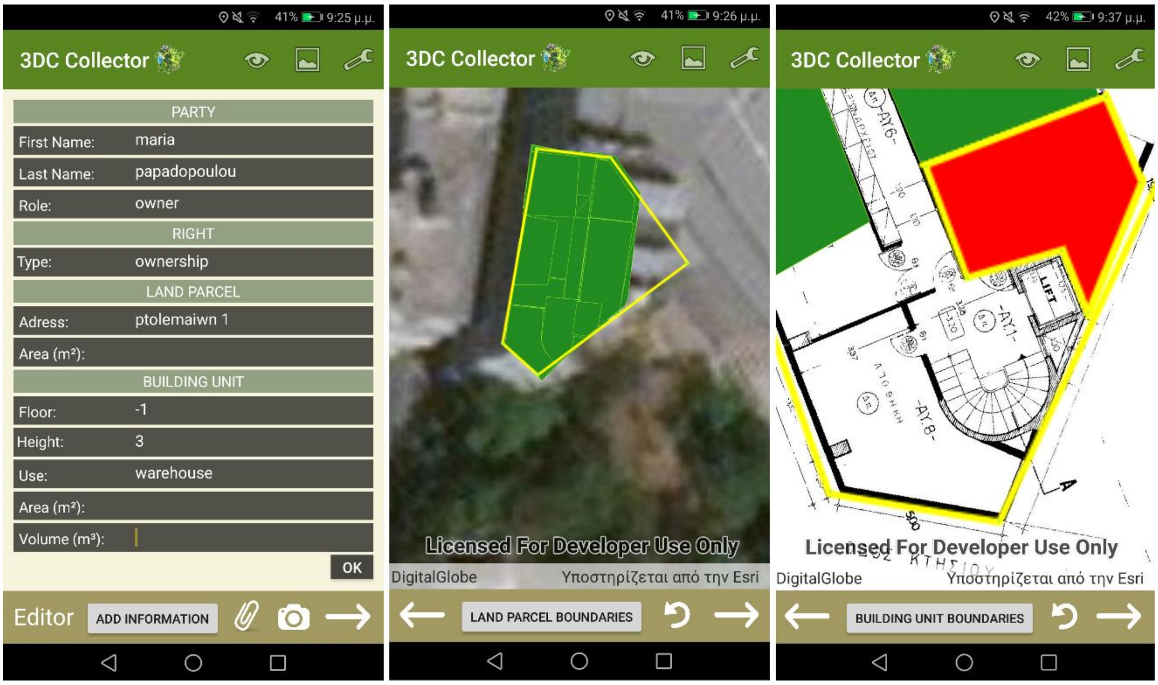


Figure 137. Example of the recording process through the developed mobile application, including (a) the insertion of the adequate cadastral information (left), (b) the polygon digitization on the parcel basemap describing the land parcel (middle) and (c) the polygon digitization on the floor basemap describing the building unit, on the basemap (right).

Each one of the volunteers was responsible for the registration of a certain number of property/building units as well as the registration of the building's shared spaces. The procedure starts with the insertion of the necessary descriptive information concerning the land parcel, the property/building unit, the type of the rights, the rights holder's personal data, as well as (in the official cadastral procedure) the insertion of verification images and legal documents, which support and empower the registration process. Next, the identification and digitization of the land parcel polygonal boundaries was conducted, by selecting its corners (as point features) on the orthophoto basemap, utilizing the land parcel digitization tool. Similarly, the identification and digitization of each property/building unit polygonal boundary outline was performed by selecting the floor basemap where the property unit is located, through the selector basemap tool, and then by selecting its corners (as point features), utilizing the building unit outline digitization tool. Figure 137 presents the described procedure. After the insertion of the necessary geometrical data the 3D visualization of the declared land parcel and the building unit, both above and below the land surface, was achieved through the selection of the 3D visualization tool (Figure 138). Finally, the collected data was stored in the developed database in the Cloud of ArcGIS Online, updating the system with the new records and the corresponding 3D property models.

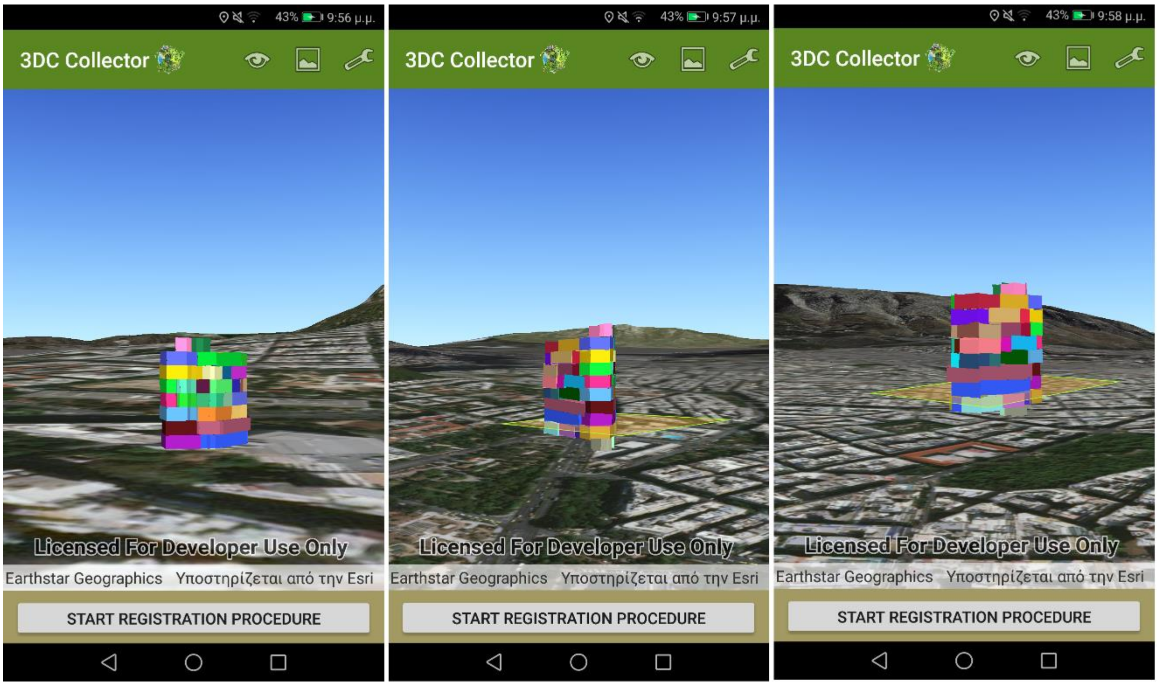


Figure 138. Generated 3D models of the declared properties above (left) as well as above and below (middle, right) the ground surface, using the 3D Model tool of the developed mobile application.

During the data collection process certain bugs, weaknesses and deficiencies were identified and highlighted by the volunteers leading to correction at the next stage of this research. The main group of errors related to the functionalities of the mobile application. Its major inability was the delay or the forced interruption of the application, during the simultaneous data storage by the users. In this case, data may not be stored in the server of ArcGIS Online, making necessary the repetition of the registration process. However, even with the existence of this error, the registration process was quite fast as the registration of each property lasted about 7-12 minutes (average recording time). The recording time varied, according to the complexity of the boundaries shape and the familiarity of the user with the smartphones devices and the mobile application. In addition, the good condition of the mobile's phone screen, directly affects both the duration and the quality of the collected data. It was observed that in case of a damaged screen, the selection of the desired points on the screen was difficult or impossible, resulting in the selection of a different point close to the desired, altering the quality of the results. This constant effort led to an increase in data collection duration.

Despite the problems identified, the collected data and the relationships between the cadastral objects, were successfully stored in the LADM-based DBMS in the Cloud of ArcGIS Online. The comparison results were satisfactory; the average accuracy deviation between the compared datasets was 0.34 m and their maximum and minimum deviation was approximately 1.17 m and 0.03 m, respectively (Figure 139). It is noted that the maximum deviation of 1.17 m, was detected in the data which were collected by a device with a defective display, strongly affecting the correct selection of the polygonal vertices (point features). Furthermore, the generated 3D models were correctly positioned in 3D space while some small shape defects were caused by the imported errors in the digitization process as well as by errors and elevation jumps in the utilized DTM.

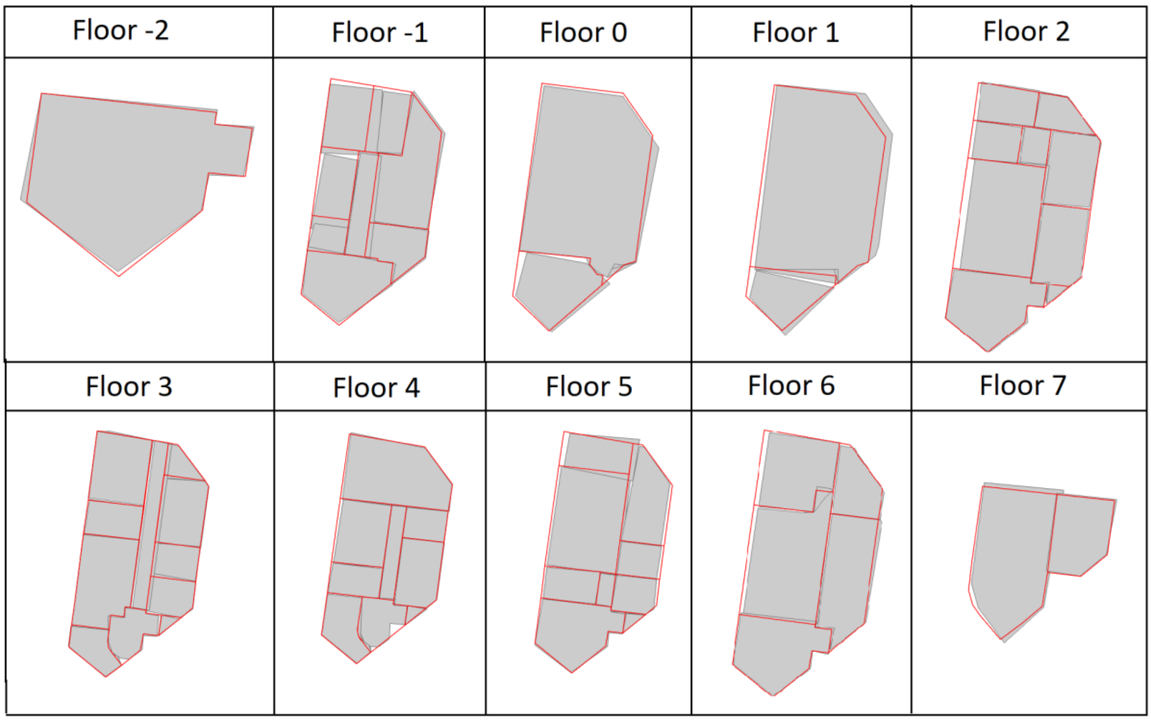


Figure 139. Comparison between the digitized polygons (in gray) and the reference data (in red), for each one of the studied building floors.

7.2.2 Geometric-oriented approach

7.2.2.1 The case study in Pagrati, Central Athens

Maintaining the same study area with the fifth experimental implementation, a Geometric-oriented approach was attempted, aiming to investigate the effectiveness of the developed technical framework in adverse cases of weak basemap availability. In this particular case study, the potentials of the embedded geometric tools of the developed mobile application were examined. The main objective of this case study as well as the type of the collected data and the methodological steps toward the completion of the registration procedure, were similar to the last test implementation. The main difference was regarding the available basemap, which in this case was only the orthophoto of the study area at a scale of 1:1000 (Figure 140).

A volunteers' team, consisted of middle-aged citizens with varied educational background, but with good digital skills, keen with smartphones technology, was chosen. The citizens' team was informed about the objectives of this crowdsourced project and subsequently was trained regarding the technical and the IT preparation, the function of the cadastral mobile application and the geometric tool, by a member of our research team with the role of the team leader. Once, this phase was completed the cadastral registration process started.

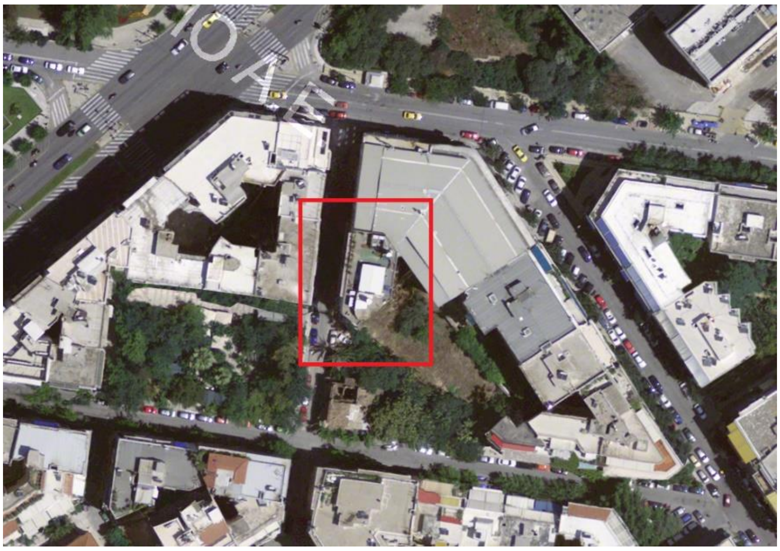


Figure 140. Orthophoto of the case-study area at the scale of 1:1000. The studied building is located within the red rectangle.

In the first step, the insertion of the adequate descriptive information regarding the declaration of rights and the right holders' data, as well as the attachment of any necessary verification images and legal documents enhancing the current declaration, was conducted by the volunteers. One of the most important factors for starting the digitization procedure was the volunteers' orientation in the 3D space and the perception of their respective location on the basemap. This may be roughly achieved consulting the GPS sensor of the mobile device, as the positioning accuracy in the interior space of the studied building was about 2-5 m. Due to the absence of a very accurate registration basemap, such as a cadastral map and professional architectural floor plans, volunteers ought to determine the position of any known building's structural (i.e. building's roof edges) or other features (i.e. fixed ground feature) on the basemap, and then determine the features (points, lines) of the desired land parcel/building unit boundaries by imposing to the known features, several geometric constraints through the geometric tools provided from the developed mobile application. In order to do so, volunteers had to measure - if needed - the distance between the known and the desired features, and proceed with the necessary geometric calculations through the mobile application. Thus, based on these principles, the identification of the land parcel and property unit boundary outline was performed, by selecting features (points) on the basemap (orthophoto) – where they were visible – and implement geometric procedures through the developed mobile application, in order to form the respective boundary polygon. As it is obvious, the determination of the building's interior cadastral units is more complicated due to their complex shapes as well as they are not visible on the available basemap. An example of the described registration procedure is presented in Figure 141, emphasizing on the registration of an indoor cadastral unit. It is noted, that during the whole procedure the team leader is at the volunteers' disposal, to resolve any questions that may emerge. Once the cadastral data are determined and collected by the volunteers, the data are stored in the cloud of ArcGIS Online, updating the system with the new records and the corresponding 3D models. The 3D visualization of the registered properties is achievable by the selection of the corresponding visualization tool (Figure 142).

Figure 141. Example of the registration process through the developed mobile application, including (top left) the insertion of the adequate information, (middle top left) the polygon digitization describing the land parcel and (middle top right, top right and bottom) the registration procedure utilizing the geometric tools for the identification/digitization of the polygon describing the building unit, on the basemap.

The developed geometrical tools provided by the mobile application were really useful for the determination and identification of the hidden boundary parts and the interior cadastral spaces, using only an orthophoto as the registration basemap. Training of volunteers regarding the function of the mobile application and the geometrical tools, was very helpful, in order to carry out the cadastral procedure. The most difficult part of their training was the understanding of the geometric tools' operation and the imposition of the geometric constraints. After presenting some examples, the tool operation was understood as it is based on simple geometric processes.

Data collection process was successfully completed, while no major problem was occurred. The overall registration procedure was relatively fast as the initial registration of each property lasted about 15-20 minutes (in average), which is hard to be achieved with traditional surveying procedures. The comparison results were very interesting approaching the current building reality, with the average accuracy deviation between the compared datasets be about to 0.48m and their maximum and minimum deviation to be approximately 1.71 m and 0.07 m, respectively (Figure 143). The maximum deviation emerges mainly in cases of incorrect usage of the geometric tools or incorrect features' identification on the basemap. Furthermore, the generated 3D models were correctly positioned in 3D space. However, some small errors presented as shape defects, are caused by incorrect selections of features position on the basemap and elevation jumps occurred in the utilized DTM.

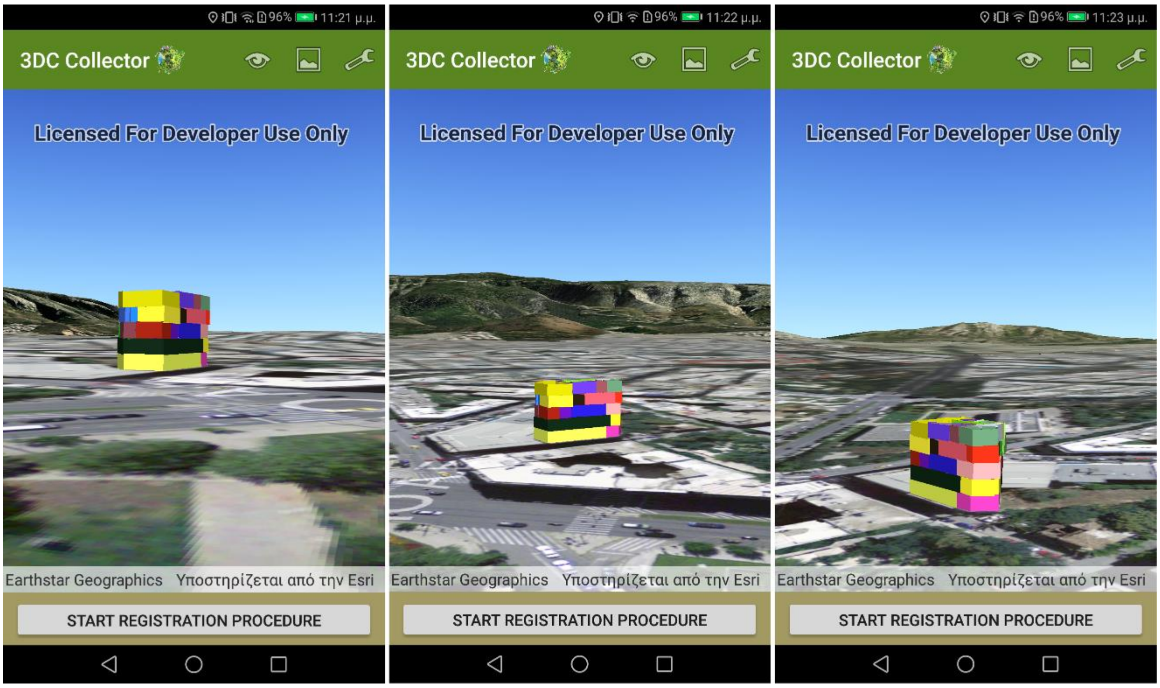


Figure 142. 3D models of the declared properties, using the 3D Model tool of the developed mobile application.

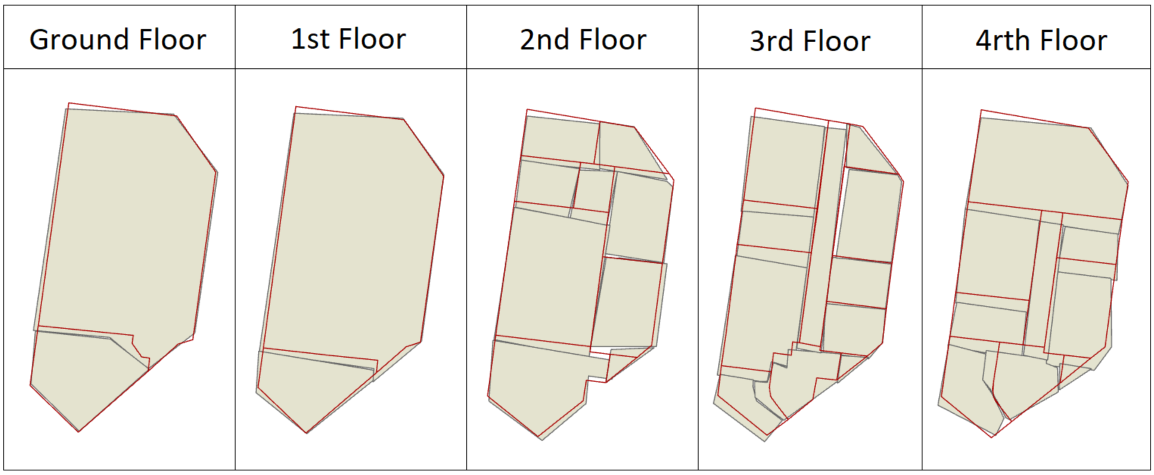


Figure 143. Comparison between the digitized polygons (in grey) and the reference data (in red), for each one of the studied building floors.

7.2.3 BIM-oriented approach

7.2.3.1 The case study in Kaisariani, Central Athens

Following the BIM-oriented approach, a test implementation was conducted in a densely structured urban area of Kaisariani in Athens, Greece (Figure 144). For this particular case study, 3D building data available from a previously successfully completed project conducted by a research team of the National Technical University of Athens, were used (Ioannidis et al., 2015). The 3D building models of a building block, were utilized as registration basemap. The models were in LoD3, describing in detail the physical characteristic of the buildings exterior. Furthermore, a new multi-storey building that will be built in the study building block, was created. For the generation of the BIM, the Autodesk's Revit software was selected, while a set of available georeferenced floor plans were utilized as reference data, following the pre-processing steps described in Section.

Figure 144. The aerial photo depicting the test area.

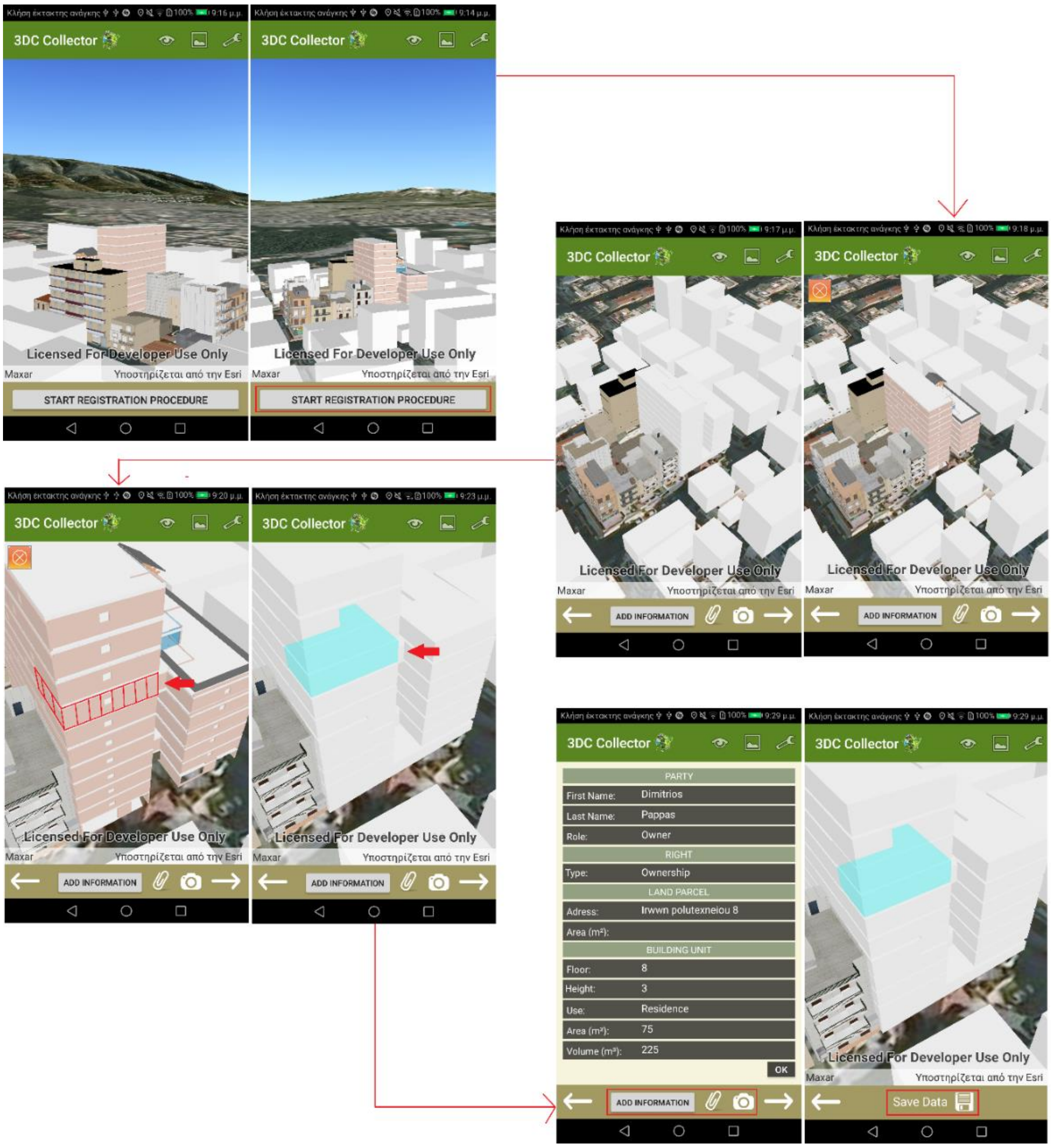


Figure 145. Example of the registration process through the developed mobile application, including: (first row) navigation throughout the 3d scene, (second row) visualization of physical and legal view of the studied building, (third row) the identification and selection of the desired property and (fourth row) the insertion of the necessary information concerning the right holder, the land parcel, the building and the building unit; and the storage of the collected data.

A team of volunteers consisted of NTUAs' students, were assumed as right holders in order to proceed with the 3D cadastral registration. As team leader a member of our research team was 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. Once the volunteers were familiarized with the mobile application the 3D cadastral registration process was started. Each one of the volunteers was responsible of identifying a specific number of property units in the BIM and declaring the necessary information through the developed mobile application.

The volunteer was able to navigate throughout the 3D building scene and view the structural and realistic characteristics of the building by enabling the physical view (LoD3) through selecting the respective tool provided through the mobile application. Once the volunteer identified the desired property unit, he/she may close the Physical view and view only the 3D legal objects (LoD1) of the studied building. By tapping on the BIM at the position that he/she assumed that his/her property was located, the 3D volume presenting the legal space where the RRRs are assigned was highlighted. Then, the user was inserted the required cadastral information utilizing the Add Information tool. For this experiment, as inserted data, the descriptive information about the rights holder (first name, last name, and type of right); and the property unit (address, area code, and use), were selected. Simultaneously, the volunteers may attach images and legal documents (in an official procedure) proving their rights, in order to verify their declaration. Once the volunteers collected the required data, they submitted their declarations, which were stored in the cloud of ArcGIS Online, updating the system with the new records. An example of the described registration procedure is presented in Figure 145.

Thus, following this sequence of registration steps, the volunteers were able to complete successfully the registration procedure, through the mobile application. The mobile application was easy to use, with the registration of each property accomplished in about 7–15 min (on average), depending on the location of the property into the BIM and the familiarity of the user with the application. In cases where the desired property unit is enclosed by other property units, its selection may be very difficult for the user. The collected cadastral data have been correctly assigned to the 3D cadastral legal objects presented through BIMs, and stored successfully in the cloud of ArcGIS Online.

7.2.4 Hybrid approach

Following the hybrid approach, 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 (Figure 146). 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.

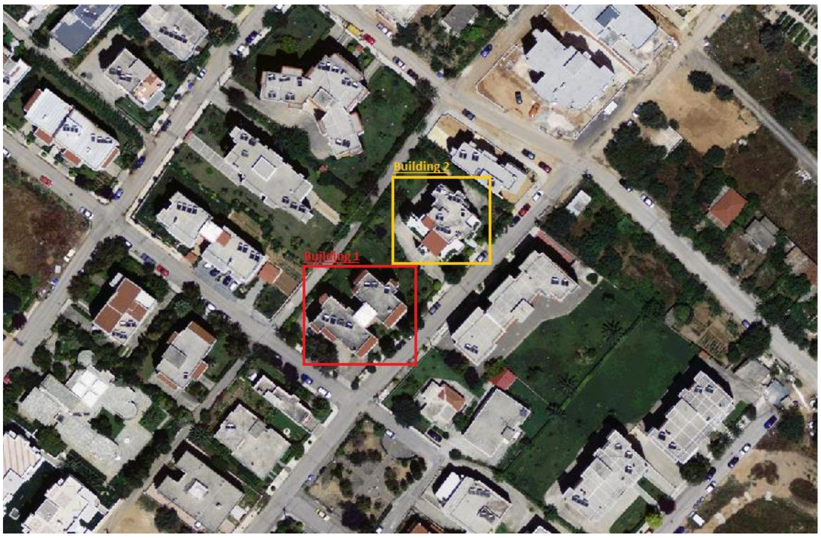


Figure 146. Orthophoto of the test area at the scale of 1:1000, depicting the studied buildings; Building 1 (in red) and Building 2 (in orange).

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 (Figure 146) 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 (Figure 147), were utilized. For Building 2, a BIM available from a previously successfully completed Diploma thesis, was utilized (Figure 148).

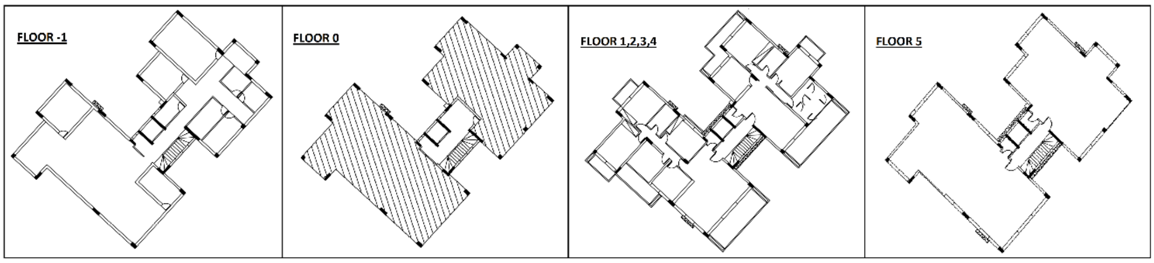


Figure 147. Floor plans of the underground floor, the ground floor, first, second, third and fourth (identical) floors and fifth floor of Building 1, at the scale of 1:200 (Source: Andritsou et al., 2022).

For the creation of the BIM, the Autodesk Revit software in combination with a set of available georeferenced floor plans as reference data, are utilized. The BIM generation was completed following the pre-processing steps described in Section 7.1.2. For this particular implementation, the identification of the exact location of the legal boundaries along the horizontal and vertical structural elements of the building, is realized according to certain assumptions based on the Greek legislation. Thus, 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;

are considered as legal boundaries.

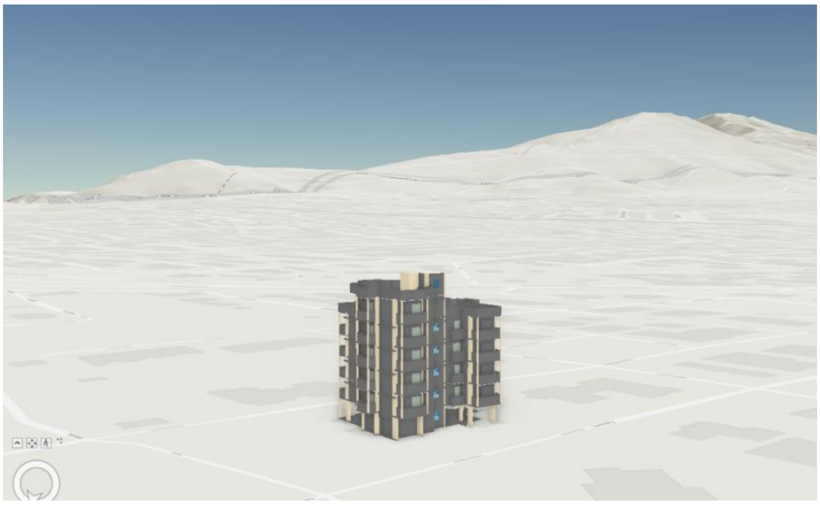


Figure 148. The BIM representing the physical counterparts of the Building 2 (Source: Andritsou et al., 2022).

Furthermore, the generated 3D legal spaces are enriched with the necessary semantic information concerning the property's RRRs, based on the developed LADM-based DBMS schema. Before the practical application begins, a set of pre-processing steps are conducted, aiming to make the available data expendable to the developed mobile application. These steps are described in Section 7.1.2 and refer to the configuration and insertion of the available data into the Cloud of ArcGIS Online. Once the required pre-processing steps are completed from the team leader, the application can be started.

For the practical implementation the proposed crowdsourced methodology is followed. A team of volunteers consisted of NTUA 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. Once the volunteers were familiarized with the mobile application the 3D cadastral registration process started.

The volunteers are able to navigate throughout the 3D scene and locate the building and therefore the building unit which they desire to register. With the GPS of their smartphones, the volunteers are able to be oriented within the study area, in order to avoid gross errors. However, the GPS is not utilized for the exact identification of the properties units boundaries, as the positioning accuracy is weak (3-6 m), especially in the interior of the buildings. Based on which of the two buildings the current property unit is located, a different method is followed by the volunteers. through choosing either the ”Manual Selection” or the ”BIM Selection”, provided by the cadastral mobile application.

For the registration of the property units of Building 1, the ”Manual Selection” is chosen by the volunteers, as BIM data are not available. Following this *”route”* the volunteers must follow a set of procedural steps. In the first step, the insertion of the adequate descriptive information regarding the declaration of rights and the right holder/s' data is conducted, through the ”ADD INFORMATION” tool of the 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. Simultaneously, the volunteers may attach images and legal documents (in an official procedure) proving their rights, aiming to verify their declaration. In the second step, 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. In the next step, the volunteers must identify the property unit boundaries (outline), 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 the desired property unit. 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 Figure 149..

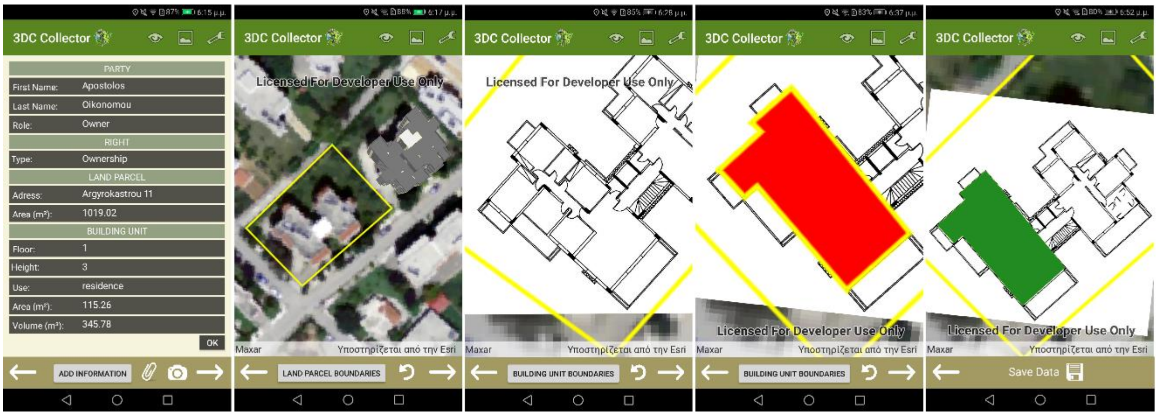


Figure 149. Example of the recording process through the "MANUAL SELECTION" option of the developed mobile application, including (from left to right): (i) the insertion of the adequate information, (ii) the digitized polygon describing the land parcel, (iii) the property unit to be registered, (iv) the digitized polygon describing the building unit, on the floor basemap, and (v) the declared building unit to be saved, in the Cloud of ArcGIS Online.

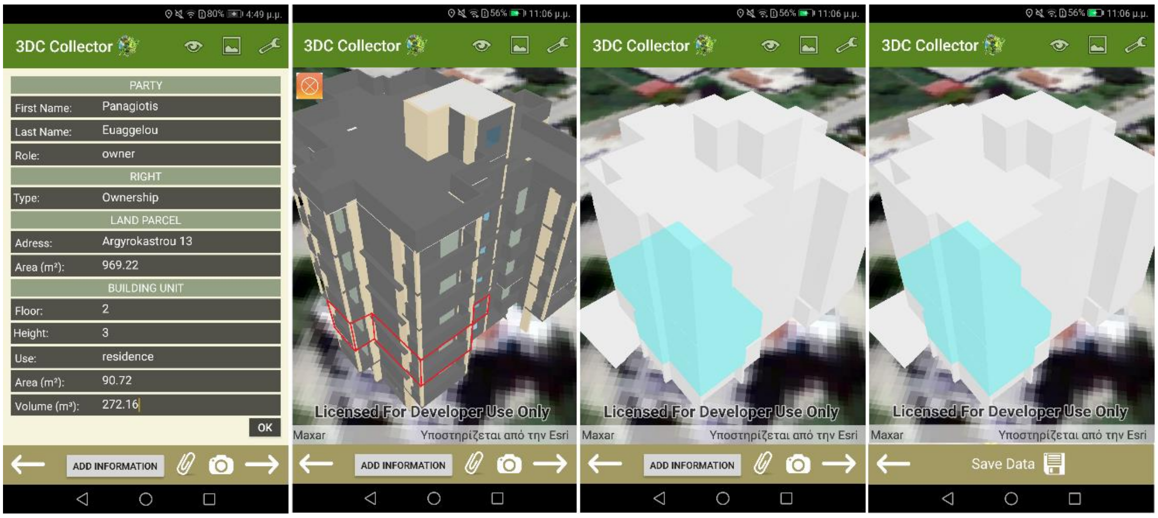


Figure 150. Example of the registration process through the "BIM SELECTION" option of the developed mobile application, including (from left to right): (i) the insertion of the necessary information concerning the right holder, the land parcel, the building and the building unit, (ii) the identification 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.

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. Following this *"route"* the volunteers follow a more simple sequence of procedural steps. The volunteers are navigated throughout the 3D building scene and view the structural and realistic characteristics of the building by enabling the physical view (LoD3) through selecting the respective tool provided through the mobile application. Once the volunteers identify the desired property unit, they close the Physical view and they view only the 3D legal objects (LoD1) of the studied building. By tapping on the BIM at the position where they assum that the desired property unit is located, the 3D volume presenting the legal space where the RRRs are assigned is highlighted. Then, the volunteers insert the required cadastral information utilizing the ”ADD INFORMATION” tool of the mobile application. Simultaneously, similar with the ”Manual Selection” the volunteers may attach images and/or legal documents. Once the volunteers collect all the required data, they submit their declarations, which 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 Figure 150. 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 succesfully 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.

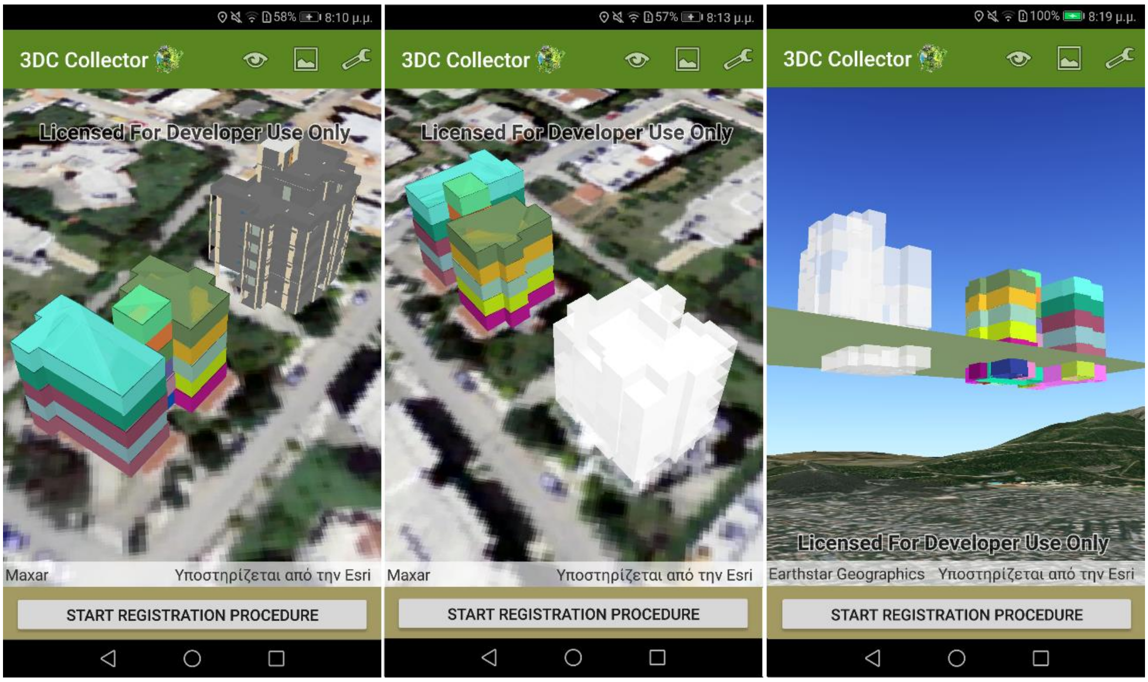


Figure 151. The generated 3D property models of Building 1 and the BIM of Building 2 in LoD3 (right), the generated 3D property models of Building 1 and the BIM of Building 2 in LoD1 (middle), and the generated 3D property models of Building 1 and the BIM of Building 2 in LoD1, both above and below the ground surface.

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) (Figure 151). 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 0.19m and their maximum and minimum deviation is approximately 0.48 m and 0.01 m, respectively (Figure 152). 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.

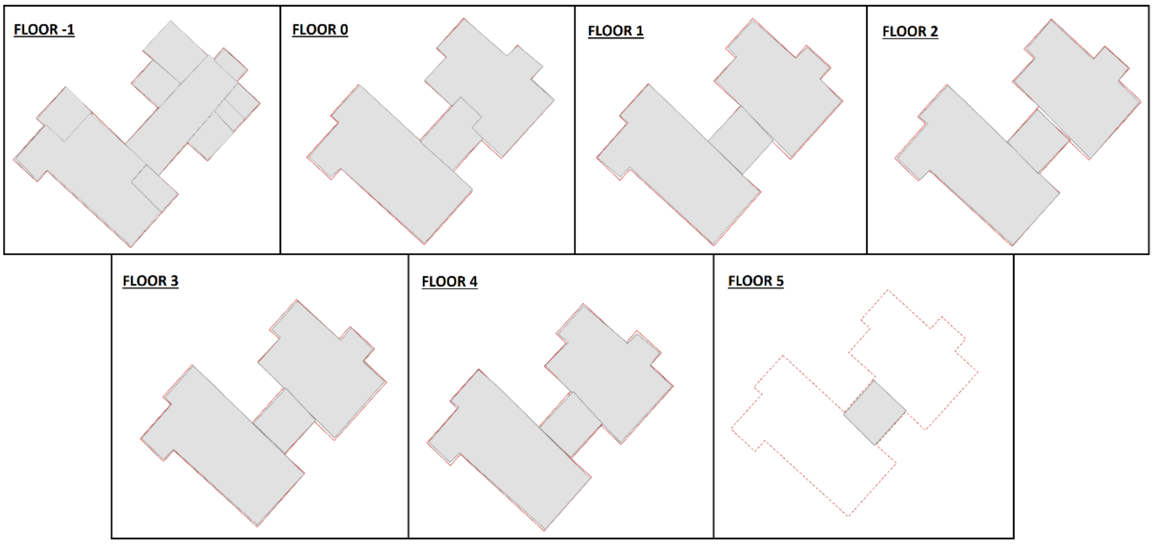


Figure 152. Comparison between the digitized polygons (in solid gray) and the reference data (in red), for each one of Building's 1 floors.

7.3 Web-based Practical Implementations

Unlike the mobile application, the web application is examined for the utilization of high accuracy BIM data, investigating the effectiveness of the second more preferable solution beyond mobile applications, for data acquisition. In this Section, two (2) experimental implementations performed in urban areas in Athens, Greece, are presented. The first test implementation, examines the effectiveness of such web solution, while in the second test implementation a more in-depth investigation was conducted, through integrating LADM specifications.

7.3.1 BIM-based approach

7.3.1.1 The case study in Kaisariani, Central Athens

The first web-based practical experiment was implemented for a multi-storey building in Kaisariani of Athens, Greece. The main interest of this test, was to investigate the functionality of the web-based technical tool, as well as the potential integration in the 3D crowdsourced cadastral framework. As registration basemap, a pre-existed BIM, representing a multi-storey building, was utilized. The generation of the BIM, had been conducted through the Autodesk's Revit software, utilizing the georeferenced floor plans, based on the pre-processing steps described in Section 7.1.2.

Data collection was performed in cooperation with the students of the SRSG of NTUA, who were assumed as rights holders. Each property was assigned to a student, who was responsible for identifying the property on BIM, and declare the adequate information through the developed web application. Once the volunteers' team informed about the objectives of this crowdsourced project and trained regarding the technical and the IT preparation, and the functions of the web application, by a member of our research team with the role of the team leader, the cadastral registration process begun.

Each volunteer was navigated throughout the 3D building scene, aiming to identify his/her property. The volunteer had a clear supervision of the scene, the structural and realistic characteristics of the building, enabling the LoD3 layer. The visualization of the building with a form similar to its reality, facilitates and make easier the recognition of a specific property. Once the volunteer identifies his/her property, may disable LoD3 and enable LoD1 layers – utilizing the layer management tool - and select the volume which corresponds to the studied property. Finally, the volunteer was inserted the necessary cadastral information, through the editor tool. When the volunteer was selected the editor tool, a drop-down list is appeared, where the declared data has to be entered. Once the cadastral data were determined and collected by the volunteers, they were submitted and stored them, in the cloud of ArcGIS Online. An example of the described registration procedure is presented in Figure 153.

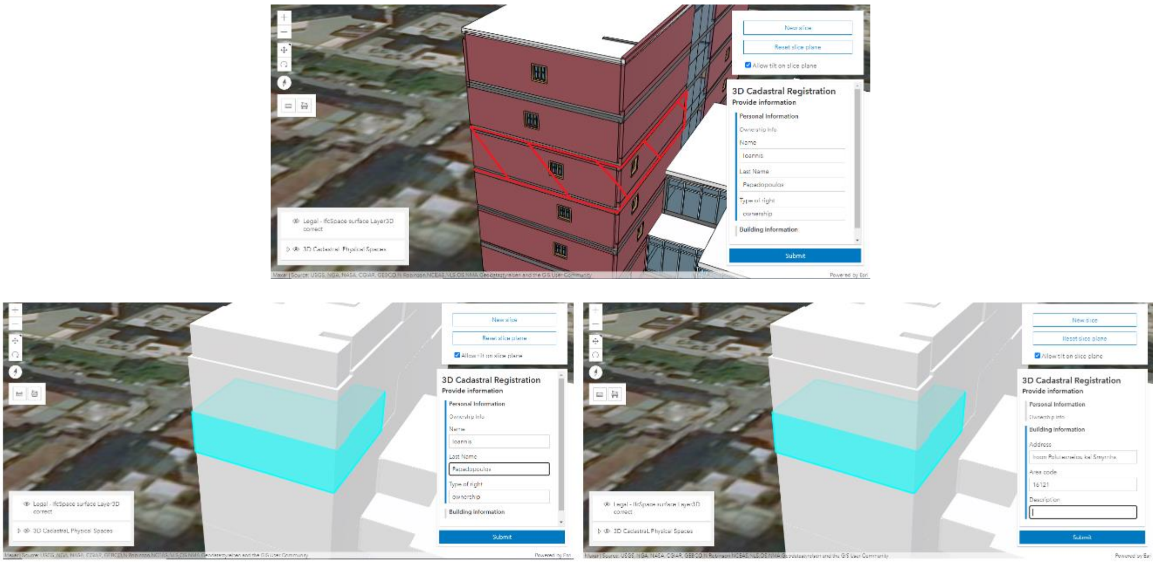


Figure 153. Example of the registration process through the developed web application, including: (top row) the identification of the desired property, (bottom row left to right) the property selection and the insertion of the necessary information concerning the right holder; and, the building.

The registration procedure was completed successfully. The web application was easy to use and the necessary information were correctly collected. The registration process was fast as the registration of each property unit lasts about 5-10 minutes (average), depending on the location of the property in the BIM and the familiarity of the user with the web environment. The required cadastral data were collected successfully and stored in the cloud of ArcGIS Online.

7.3.1.2 The case study in Kaisariani, Central Athens

Remaining in the same study area and expanding the number of the property units to be registered, the second web-based practical experiment was implemented (Figure 154). At this stage of the investigation the research had been integrated the LADM standard, as the main data model for structuring the cadastral database. For this particular investigation, the same 3D building models in LoD3, utilized in a previews case study (in Section 7.1.2) were utilized.

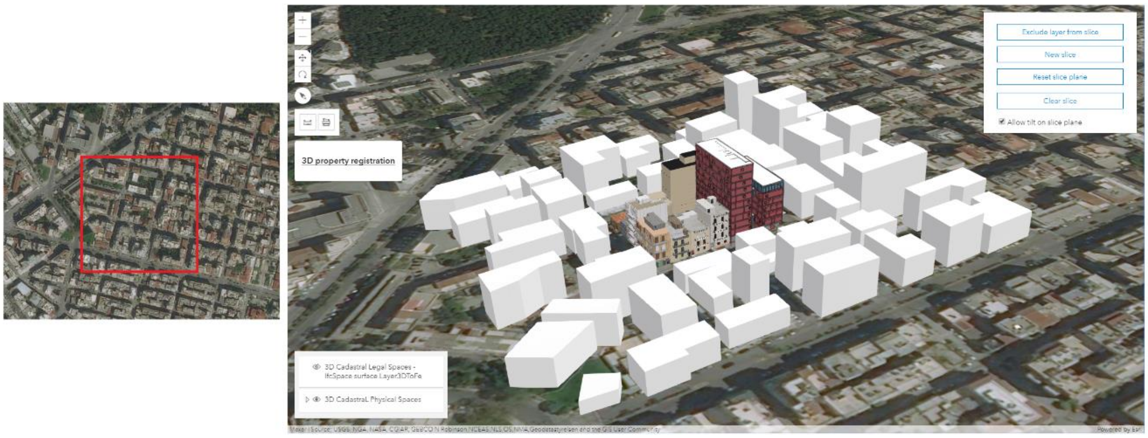


Figure 154. The aerial photo of the test area (left) and the 3D models of the studied and neighboring buildings (right).

For research purposes, a team of students at the SRSG of NTUA, were assumed to be rights holders and proceeded with the 3D cadastral registration of multiple overlapping property units. Each volunteer undertook the responsibility of identifying specific property units in the BIM and declaring the necessary information through the developed web application. For this experiment, the collected data included the property entity/volumetric object from the BIM that corresponded to the studied property unit; the descriptive information about the rights holder (first name, last name, and type of right); and the property unit (address, area code, and use). Once the pre-processing steps were completed and the volunteers were informed and trained, the test implementation started. An example of the described registration procedure is presented in Figure 155.

Finally, the registration procedure was completed. The web application did not create any registration barriers for users. The registration of each property was accomplished in about 6–12 min (on average), while the necessary cadastral data were collected successfully and stored in the LADM-based database, with correctly generated relationships.

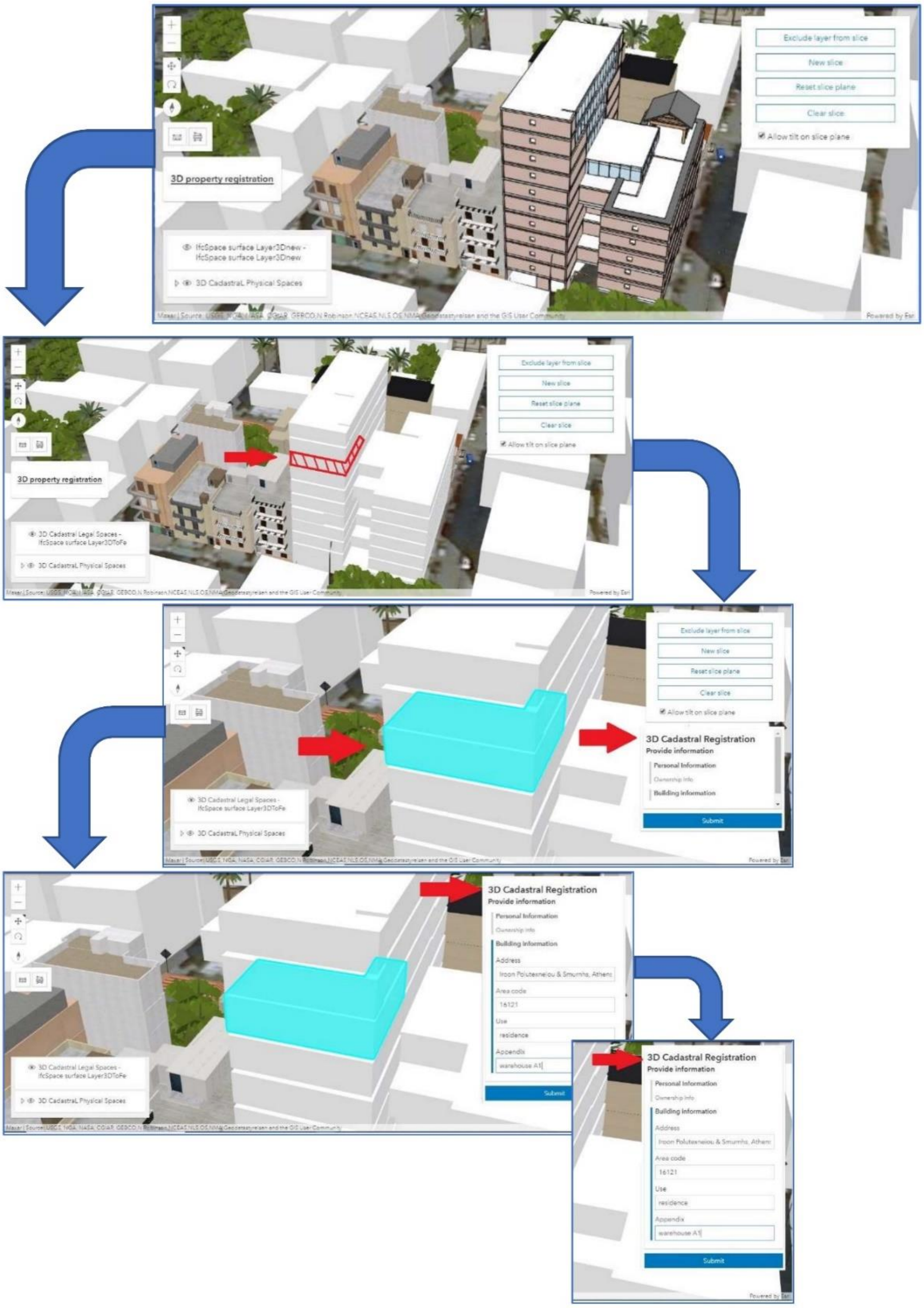


Figure 155. Example of the registration process through the developed web application, including: (first row) the identification of the desired property; (second row) the property selection; (third row) the insertion of the necessary information concerning the rights holder; and (fourth row) the building.

7.4 Assessment of the Results

In this Section, an evaluation of the developed technical framework, based on the outcome of the implemented practical experiments and the volunteers' feedback, is conducted.

A particularly important feature of the developed framework is the adaptation to the available geospatial background. The (re-)use of BIM data lead both to very accurate registrations, while at the same time lays the foundation for the implementation of a highly-accurate 3D cadastral system. In addition, the use of architectural floor plans or orthophotos of high accuracy, contribute to the generation of an accurate outcome, preserving right holder's property rights. Furthermore, the developed geometric tools expand the range of applications and the perspectives of the developed cadastral solution, as they allow the utilization of low accuracy platforms (aerial photo, OSM etc.) as registration basemaps. Especially, in the absence of architectural floor plans, the registration of the interior cadastral spaces is weaker. The utilization of geometric constrains for the identification of hidden features, is indispensable. At this point, right holders' participation is of great importance, increasing the reliability of the collected data, as there is no one more suitable to indicate the property boundaries than its own resident/occupant (Goodchild, 2007a; b).

During the practical experiments volunteers seemed to be very receptive to the crowdsourced 3D cadastral project and supportive for its implementation in real circumstances. As emerged, their will to participate in this crowdsourced procedure was empowered by the possible reduction of the time, costs and errors of the required cadastral procedures, enabling the real estate market to start operating again. However, public recruitment in such crowdsourced procedures is not easy. The contributors/rights holders have to be motivated in order to participate and produce reliable results. Following gamification strategies, a reward for the rights holders' participation in the cadastral procedure, such as a discount on taxes or registration fees for the most active, may strengthen the rights holders' motives in order to ensure the smooth, robust and efficient implementation of the crowdsourced process (Gkeli et al., 2019; Apostolopoulos et al., 2018). After reviewing volunteers about their opinion on this matter, there seemed to be a positive reaction about establishing such rewards policy.

After a proper training, volunteers were able to interact and collect data through the developed applications, quite easily. The volunteers agreed that the developed applications are easy enough to be learned and used, as their interfaces are designed appropriately, simplifying the registration procedure. The prototype mobile application, developed in the context of this doctoral dissertation, utilizes the current algorithms and techniques in 3D reconstruction. Through using parametric 3D modelling (Model-driven approach) techniques, the 3D modelling of the cadastral object can be successfully implemented automatically, defying the known difficulties in 3D modeling that make it a time consuming and tedious process. Both the developed mobile application and web application, provide a user friendly environment for the implementation of 3D cadastral surveys. Rights holders / Users do not need to have a certain level of 3D modelling skills in order to contribute to the registration procedure. The applications' interfaces are 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.

The developed mobile and web applications are distinguished by learnability, efficiency and memorability, but there are some parameters that need to be reconstructed and updated, in order to minimize errors and maximize users' satisfaction during the registration process (Nielsen, 2012). During the data collection process certain bugs, weaknesses and deficiencies were identified and highlighted from both the volunteers and the team leaders. The main group of errors related to the functionalities of the mobile application. Its major inability was the delay or the forced interruption of the application, during the simultaneous data storage by the users. In this case, data may not be stored in the server of ArcGIS Online, making necessary the repetition of the registration process. Nevertheless, this problem concerns the waiting and (re-)connection time between the mobile application and the online database and it can be resolved through some minor changes in the source code of the mobile application. Furthermore, another difficulty was identified in the use of the geometric tools of the mobile application, which depends a lot on the volunteer's digital skills, age and perception of geometry matters. The absence of familiarity with mobile devices, which mainly may refer to elderly people, may have a negative effect on the procedure's outcome. The volunteer's inability to be oriented in the indoor 3D space and identify known features on the basemap, may lead to incorrect point selection, affecting greatly the achieved results. Also, the screen size of the mobile device seems to affect the data collection process. A device with a wide screen, such as a tablet, may facilitate the identification of the property boundaries and make the registration procedure much easier for the volunteer.

Due to the heterogeneity of the contributors both the methodology and the technical system, have to be carefully structured in order to provide a qualitative and reliable outcome. Data quality is a challenging topic of primary importance for the effectiveness and reliability of a cadastral procedure. Among various quality standards, ISO 19157 (2013) present six (6) spatial data quality elements (completeness, logical consistency, thematic accuracy, temporal quality, positional accuracy, and usability) in order to assess the quality of a product. As the crowdsourced technical framework, is structured based on the international standard of LADM, it turns out that the collected data were well attributed, distinguished and related by logical rules, maintaining the corresponding time stamp regarding the time period of their capture. Also, as the responsibility for the initial data collection process is transferred to the rights holders, who know better the boundaries and location of their properties, the reliability of the cadastral surveys is increased by the elimination of gross errors (Basiouka & Potsiou, 2012a; b; Mourafetis et al., 2015; Apostolopoulos et al., 2018; Molendijk et al., 2018; Gkeli et al., 2016; Rahmatizadeh et al., 2016). Thus, the collected data are characterized by completeness, logical consistency, thematic accuracy, temporal quality and reliability.

The registration process is fast enough and it is completed successfully without major problems detected in each practical implementation (Table 3). Through the crowdsourced approach presented in this research, the registration of each property varies from 3 to 20 minutes, according to the complexity of the property's shape, the available geospatial infrastructure and the volunteer's digital and comprehensive skills. However, the duration of the 3D crowdsourced cadastral surveys is quite low, which is hard to be achieved with traditional surveying procedures. The role of the team leader was significant, resolving any questions that volunteers had and thus saving valuable time. Considering the simultaneous registration of several different properties, it is obvious that the time of the required field surveys can be dramatically reduced in the formal cadastral procedures.

Nonetheless, in such crowdsourced projects there is a trade-off between time and achieved accuracy. As it proved by the practical experiments, the achieved (average) accuracy of the collected data may not reach the high accuracy level of traditional topographic field surveys, but it was very satisfactory considering that the data were collected by non-professionals and with low-cost equipment (Table 4). It is important to state that the achieved accuracy may meet the accuracy specifications of several countries, as Greece, where the current accuracy specifications of the Greek Cadastre for urban areas is 0.71 m (RMSExy). This requirement is covered in the majority of the implemented case studies, enhancing the reliability and perspectives of the developed technical framework. The existence of some accuracy outliers, such as the maximum accuracy deviation of 1.17 m and 1.71 m, is due to either a damaged mobile phone's screen or misunderstanding of the depicted elements of the basemap, leading to false boundary identification and digitization. However, as has been highlighted previously (Apostolopoulos et al., 2018; Gkeli et al., 2016), the results of a crowdsourced procedure may be greatly improved after a proper training and briefing of the volunteers/right holders by a trained team leader or a professional surveyor prior or during the 3D cadastral surveys. Nevertheless, the main objective of this fit-for-purpose approach, is to safeguard citizens' rights, while the accuracy may be improved gradually.

Approach		**Practical Experiment**	**Time / Duration (min)**
Mobile-based	Cartographic - Oriented	Test 1	3-5
		Test 2	3-7
		Test 3	5-7
		Test 4	10-12
		Test 5	7-12
	Geometric - Oriented	Test 1	15-20
	BIM - Oriented	Test 1	7-15
	Hybrid	Test 1	"Manual Selection": 8-20 "BIM Selection": 7-14
Web-based	BIM - Oriented	Test 1	5-10
		Test 2	6-12

Table 3. Duration of the implemented 3D practical experiments.

Approach		**Practical Experiment**	**Accuracy (m)**		
			Average	Min	Max
Mobile-based	Cartographic - Oriented	Test 1	0.15	0.03	0.36
		Test 2	0.17	0.01	0.42
		Test 3	0.17	0.03	0.49
		Test 4	0.21	0.03	0.75
		Test 5	0.34	0.03	1.17
	Geometric - Oriented	Test 1	0.48	0.07	1.71
	BIM - Oriented	Test 1	BIM accuracy	BIM accuracy	BIM accuracy
	Hybrid	Test 1	BIM accuracy & 0.19	BIM accuracy & 0.01	BIM accuracy & 0.48
Web-based	BIM - Oriented	Test 1	BIM accuracy	BIM accuracy	BIM accuracy
		Test 2	BIM accuracy	BIM accuracy	BIM accuracy

Table 4. Achieved accuracy of the implemented 3D practical experiments.

Furthermore, the produced 3D models were properly placed in 3D space, while some small shape defects were caused either by the imported errors in the digitization process or by irregularities of the utilized DTM. These irregularities usually refer to incorrect altitudes of certain points in the DTM, leading to significant errors. However, this drawback may be resolved through utilizing a more accurate DTM adapted to the local surface of each country and not to the entire globe, such as the one provided by ESRI and used for the current practical implementations. Besides that, it is worth mentioning that the generated 3D models were accompanied by the corresponding descriptive cadastral information, stored in a correctly structured (LADM-based) DBMS, facilitating the post-processing and querying procedures, which are useful in various applications.

7.5 Conclusions

A short presentation was given on the operation of the developed technical framework for the initial implementation of 3D crowdsourced cadastral surveys. Based on this experience, it appears that the developed framework has many Strengths, Weaknesses, Opportunities and Threats (SWOT) (Table 5).

Strengths	Weaknesses
- Various platforms may be used (orthophoto, aerial photo, OSM)	- Depends on volunteer’s digital skills, age, knowledge
- Low-cost equipment	- Lower geometric accuracy depending on the basemap used
- Fast implementation	- Dependence on visible cadastral features/boundaries
- Reliable/Crowdsourced data	- Need for a wide screen device
- Immediate data collection/ create up-to-date DBMS	
- LADM standard	
- M-services/ IT tools – easy-to-use	
-Automated 3D modelling	
- Produce preliminary 2D/3D cadastral data	

Opportunities	Threats
- Development of initial 3D cadastres everywhere	- Conflicted expert opinions for the reliability of the derived data in the case of using low accuracy basemaps
- Low investment cost for the commencement of 2D/3D cadastral surveys	- Acceptance of lower geometric accuracy-if basemaps of lower accuracy are used- based on the countries’ accuracy specifications
- Potential to reduce property disputes / transparency	- Misalignment with official records or existing systems
- Reliable/Crowdsourced data	

Table 5. SWOT analysis results on the proposed crowdsourced technical solution

The developed framework aims to provide a more generalized procedure adjustable to the available cartographic infrastructure and financial situation of each country, including even regions that still lack a 2D cadastral data registration. It consists an example of a reliable, affordable, fast, qualitative and easy way for the initial implementation of a fit-for-purpose, well-functioning 3D cadastre, even in developing countries. Depending on the availability of the cartographic infrastructure, the accuracy of the results may vary. In countries where an orthophoto can be provided, the achieved accuracy of the parcel units is similar to the accuracy of "triple A" 2D cadastres. If the rights holders have floor plans that are compiled by engineers who have constructed the buildings, the achieved accuracy of the 3D cadastre is satisfactory. In case where BIM data are available, the achieved accuracy reach high requirements, providing fundamental data for the implementation of an accurate and reliable 3D cadastral system. If BIM data or floor plans compiled by engineers do not exist, there are other options to proceed with 3D registration (i.e. geometric tools) but with reduced geometric accuracy of the final product. However, it is always an option to improve it at a later stage. What is most important in order to meet the Sustainable Development Goals (SDGs) in time is not the final geometric accuracy of the 3D property unit models, but the completion of the registration of all units and rights as quickly as possible by an affordable and inclusive method, while providing security of rights in the most reliable way according to existing funding.

Chapter 8

General Conclusions

8.1 Discussion and Contribution Highlights

The overwhelming technological revolution of recent decades has affected intensively the way that geospatial data acquired, maintained, analyzed, visualized, used and disseminated. These massive changes could not but influence the way that National Mapping Agencies (NMAs) work, to develop modern Land Administration Systems (LAS). So far, traditional Cadastres are mainly based on 2D maps which are inadequate to provide information about the legal status of real estate in cases of multi-storey land use with overlapping and complex property issues, retaining some significant gaps. Incorrect registrations, mistaken declarations, misunderstandings and multiple disputes concerning these property rights, are only some of the consequences of the poor management of the increasing multidimensional property rights. The sustainable management of this complex reality requires transparency and credibility in the determination of property rights at every level, in vertical and horizontal dimensions, above and below the ground surface.

To get closer to resolving these issues a 3D LAS is needed in order to provide Accurate, Assured and Authoritative (AAA) information about the multi-dimensional property RRRs. With the advent of 3D Cadastres, 3D property RRRs of stratified objects can be described in detail, creating a secure and transparent framework for more effective management and use of 3D space. Despite the introduction of the international standard of LADM (LADM ISO 19152) in 2012, no restrictions have been placed on the accepted data types, 3D geometries and representations of the cadastral objects, retaining the investigation in this field still active. The adherence to traditional cadastral surveys with high financial and time requirements prevents the immediate completion of such a property registration system, intensifying current problems and prohibiting the well-function of property markets in several countries. A fit-for-purpose approach may constitute a potential solution, ensuring that both the developed and developing countries may appropriately build functional LASs within a relatively short time frame and affordable costs, in order to meet the 2030 UN Agenda SDGs.

Low-cost equipment, IT tools, crowdsourcing techniques, artificial intelligence, automation, mobile services (m-services), web services, open-source software (OSS), technical models and international standarts, are some of the key drivers supporting this effort; while simultaneously lay the foundations for a widely coveted 'smart' future world. In this context, the aim of this dissertation has been to harmonically integrate the current research trends and technological innovations, to provide an affordable, timely and flexible technical framework and a methodology for the initial registration, modelling and visualization of 3D crowdsourced cadastral data anywhere, exploiting the available geospatial infrastructure of each country and including regions that still lack registration of 2D cadastral data. The research explored in depth the theoretical and technological background that required to support this venture, ensuring its alignment with the global efforts towards this direction. The precise investigation and identification of the different types of legal objects was out the scope of this study.

The research has been focused on the most expensive and time-consuming phase of the implementation process, which is the 3D cadastral data acquisition including the semantic information of the ownership status and other rights, as well as the 3D modelling and the visual representations of the property units. As the available geospatial infrastructure, financial resources and Cadastre progress differ from country to country, the main objective of this dissertation was to provide an approach adaptable to the current situation of each country. In this context, one of the first issues that have been addressed from the research was the investigation of the alternative data sources that can be utilized for the collection of 2D and 3D crowdsourced cadastral data. The type of the registration geospatial background is crucial as it directly affects the quality of the collected data and the final outcome. A recent orthophoto overlaid with the architectural floor plans of the buildings units, an updated cadastral map or BIM data – if available – consist the best geospatial options studied in this research. In the absence of such accurate registration background, other options may be also utilized, such as aerial photos taken from various platforms (e.g., UAVs), other maps, or even the OpenStreetMap (OSM), with gradually descending precisions.

At the same time, the significant advances that have been made so far in the field of digital technology, photogrammetry and computer vision have created the conditions for the impressive development of innovative algorithms and techniques for buildings detection, extraction and reconstruction, providing valuable 2D and 3D geospatial information. 3D cadastral data acquisition and modelling presupposes the establishment of a cooperative connection between the fields of Cadastre, photogrammetry and computer vision. In the cadastral context, photogrammetric methods have been mainly utilized for the compilation of basemaps, namely orthophotos, for recording physical features of the landscape that are visible from the air. In this context, this dissertation has explored the current reconstruction algorithms and techniques, investigating: (i) the potential provision of accurate and reliable 2D and 3D geospatial data able to assist 3D cadastral surveys; and (ii) the most appropriate 3D modelling approaches that can manage succesfully weak and incomplete data, as crowdsourcing data are typically characterized. The main focus of the developed methods has been on man-made scenes, namely buildings, which are the receptacles of the individual property units.

For the provision of accurate and reliable registration backgrounds, the interest of this research has been focused on the utilization of geo-referenced aerial imagery and dense point clouds, produced through dense image matching techniques. Two distinct methodologies have been developed: (i) a deep learning algorithm and a methodology able to automatically detect, extract and vectorize buildings outlines, utilizing a relatively small dataset of aerial georeferenced imagery, and (ii) a methodology the automated detection, extraction and reconstruction of noisy buildings' roof tops in densely urbanized areas, using dense point cloud data and photogrammetric techniques. In addition, the research exploring the best-fitted approach for 3D modelling of crowdsourced data, has focused on promoting the aspect of automation in the modelling processes with the aim to enable non-experts to contribute. A 3D parametric modeling algorithm was developed to provide the 3D models of the registered cadastral objects. The algorithm receives as input: (i) the digitized polygon representing the footprint of the declared cadastral object, and (ii) a numeric value representing the vertical extent of the cadastral object (height). The algorithm processes the inserted data through a footprint-based parametric modelling approach, and provide the 3D volumetric geometry of the current cadastral object, at LoD1.

The designed technical framework was based on GIS, database and network technology, which cooperation provides better organization, access, maintenance, and updating of global GIS systems, such as Cadastres. Especially, the use of mobile GIS technology and wireless services extends the recording capabilities of 2D and 3D information, since not everyone has access to wired internet. This facilitates, simplifies and speeds up the registration procedure. The development of the crowdsourced methodology was based on the lessons learned from recent crowdsourced mapping projects and findings concerning the influencing factors affecting the motivation, the recruitment of citizens and the quality of the collected data. In this context, the research has explored the potentials of crowdsourcing techniques and mobile GIS technologies in 3D cadastral surveys and developed an alternative methodology, aiming to establish an active cooperation between right holders, technicians and professionals through the introduction of team leaders, briefing/motivation/training sessions and real-time assistance during the cadastral registration.

The utilization of crowdsourcing techniques and m-services has already been achieved in developing 2D cadastral surveying procedures. However, their introduction into 3D Cadastres poses additional challenges, especially in the modelling of the 3D objects and the information related to the 3rd dimension. So far, there is a limited number of cadastral-oriented mobile applications, which is almost eliminated when the third dimension is entered in this context. This dissertation explores the current 3D crowdsourced applications of the real world, m-services, web services and open-source softwares and platforms, investigating the prerequisites and requirements for the development of a 3D crowdsourced cadastral application. Two discrete cadastral applications with different functionalities have been developed: (i) a mobile application, and (ii) a web application. The mobile application serves the identification and collection of 3D geometric and descriptive data, utilizing the available 2D or/and 3D geospatial information, along with digitization and geometric tools; the automatic generation of 3D land parcel and property unit models as block models (LoD1), using Model-driven approach – when needed; the generation of the corresponding KML objects (land parcel, building unit) – when needed; the registration of the cadastral data and their relationships within a 3D (LADM-based) cadastral geodatabase; the visualization of 3D cadastral objects in real-time, on the mobile phone's screen. In addition, the web application includes less functions but offers some essential tools needed for viewing and manipulating technical models, such as BIM data; tools for collecting, storing and updating the 3D cadastral information regarding the properties RRRs and the right holders; enables the addition of new or updatance of already existed registrations and relationships within an LADM-based cadastral geodatabase. The development of these applications was carried out with the aim of supporting the developed framework. Nevertheless, this dissertation mainly supports the use of the mobile application for the implementation of cadastral works. The development of the web application was carried out in order to explore the possible alternative platforms that can be exploited.

The rapid development and expansion of smartphones with various integrated sensors, cameras and internet access facilitates the 3D cadastral registration process, promoting their further development in this field. In particular, the GPS / GNSS sensors included in smartphones have contributed significantly, as a key supporting factor, to several location-based mapping applications. However, in terms of the indoor environment their function is problematic, as the GPS / GNSS signal is weak, introducing large positioning errors. It is obvious that in the case of the 3D Cadastre the separation of the interior of the building and the definition of the individual 3D cadastral objects included in it, is crucial. Especially in cases of the absence of an accurate and qualitative registration background, this process is more difficult. However, the recent evolution of inertial navigation systems and radio signals, such as WiFi, Bluetooth, 3G, UWB sensors, etc., may facilitate the confrontation of this indoor positioning weakness. In this context, the research has explored new methods for the reliable indoor positioning, investigating the potential integration of innovative machine learning techniques and Bluetooth technology for the establishment of an IPS; in order to automatically provide the position of the mobile device within an indoor environment, aiming to add more intelligence to the developed 3D crowdsourced cadastral framework.

Another issue addressed in this research was about the effective management, maintenance and updating of 3D cadastral data and models. The selection and use of a commonly accepted data structure is recommended, to enable data interoperability and facilitate their potential integration into the current official cadastral systems. The international standard of LADM has selected to structure the collected crowdsourced data. As LADM does not define the acceptable 3D geometries and representations for the 3D cadastral objects, this research has focused on exploring the potential modifications and extensions of the basic LADM schema, to incorporate not only the descriptive cadastral information but also the 3D geometry of the cadastral objects. In this context, the developed LADM-based conceptual schema was extended in order to embed the geometry of (i) an open polygonal structure, representing the 3D spatial extent of the RRRs relating to the land parcel, and (ii) two individual closed polygonal structures, representing the spatial extent of the RRRs referring to the property / building units. The latter two relate to the volume of the property unit and each one is defined as: (i) a set of polygonal features that constitute a closed polygonal structure, and (ii) a multi-patch feature.

8.2 Main Conclusions

In this section, the basic conclusions carried out in the context of this dissertation are presented. These conclusions concern the methodology and technical framework for the initial acquisition, registration, management, maintenance, modelling and visualization of 3D crowdsourced cadastral data; as well as, the potentials of the developed methods, methodologies and algorithms for the detection, extraction and reconstruction of buildings, to be integrated in the developed 3D crowdsourced cadastral framework. Initially, some general conclusions are reported, while then the main findings related to the developed methodology, technical framework and data quality are presented.

8.2.1 General outcomes

- The research indicated that crowdsourcing techniques may be a good practice for assisting viable projects and fit-for-purpose solutions requiring the fast and economic acquisition of 2D or/and 3D geospatial information. Crowdsourcing claims a key position as a tool for collecting and sharing geospatial information through the internet.
- Mobile devices and especially smartphones, have a prominent role as a data capturing tool in the majority of crowdsourced projects, enabling the acquisition and dissemination of data remotely, facilitating users to contribute from distance.
- The generation of 3D models can be accomplished by individuals without special skills through open source solutions with enhanced automation. So, a person just needs to be interested in contributing, to easily create a 3D building model.
- Especially for crowdsourced applications, the use of Model-driven instead of Data-driven reconstruction methods is usually preferred, since they are characterized by higher stability, maintenance of the topology, less computational costs and offer an easy solution for 3D modelling that can be adopted by non-experts, leading to reliable results.
- Low-cost equipment, crowdsourcing techniques, autonomous surveying techniques, automated feature extraction, m-services, web services, OSS, machine learning techniques, BIMs and LADM, are some of the key technological drivers of a coveted ‘smart’ future world; that signify a new era of acquiring, recording, modeling, visualizing, maintaining, updating, exchanging and disseminating of both 2D and 3D cadastral data, reducing the costs, time and human resources needed for the compilation of the cadastral surveys.

- 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 a 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.

- Through the developed technical solution, the initial establishment of a functional 3D cadastre is feasibly in a short time-frame, supporting 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.

- It is noted that with some minor alternations, the developed technical framework may be exploited for the fast and reliable generation and dissemination of 2D and 3D geospatial context for a wide variety of applications beyond 3D Cadastres, such as Digital Twins, urban planning, GIS, security applications, navigation, risks management, etc.

8.2.2 Outcome over methodology

- The developed methodology consists an innovative approach, as it is the first attempt introducing crowdsourcing in 3D cadastral surveys. The proposed process consists of a series of simple and flexible stages, that can be completed quickly with the aid of low-cost technologies, by non-professionals.

- Introducing citizens' participation, low-cost modern IT tools and crowdsourcing techniques in the 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 gross errors.

- Our research indicated that through the developed crowdsourced framework the registration of each property can be completed in minutes (for typical properties from 3 to 20 minutes), based on the complexity of the property's shape, the available geospatial infrastructure and the volunteer's digital and comprehensive skills. The duration for the registration is obviously shorter than that of traditional topographic processes. Considering the simultaneous registration of several different properties, it is obvious that the time of the required field surveys can be dramatically reduced in the official cadastral procedures.

- The establishment of a two-way model of cooperation between right holders/citizens, volunteers, technicians, experts/surveyors, inspectors and the national mapping agency, speed up the implementation processes and increase their reliability.

- Through the establishment of briefing and training sessions as well as the infield active support by the team leaders, the reliability of the collected 2D and 3D data can be increased, reducing at the same time the duration of the cadastral process.

- The research showed that the recruitment of right holders to participate in a cadastral crowdsourced project can be empowered by providing appropriate incentives. Rewarding right holders with a discount on taxes or registration fees seemed to be a powerful incentive. Following gamification strategies, a reward policy can be established, strengthening the rights holders' motives in order to ensure the smooth, robust and efficient implementation of the crowdsourced cadastral process.

- In this dissertation the use of a mobile GIS application is preferred. The selection of a mobile GIS application is very helpful as a mobile device allows the right holders to move throughout the property and collect directly the necessary information/measurements. The selection of a mobile application and wireless services widens the implementation range of the developed crowdsourced approach as not everyone has access to a wired internet. Thus, this approach may be applied for both the developed and developing countries, allowing their access to a trusted land registry, ensuring their rights.

- The exploitation of various 2D and 3D data sources as registration background, increase the flexibility and the adaptability of the developed methodology to the current needs, legislation and proprietary situation of each country.
  - Exploiting the rich 3D content of BIM can lead to very accurate registrations laying the foundation for the implementation of a highly-accurate 3D cadastral system. Especially, through the re-usage of already existed BIM can also retain the cost of the implementation process low. Either way, the utilization of BIM can provide a better visual representation of the real environment facilitating the right holders to locate and indicate their properties on the model.
  - The utilization of architectural floor plans or orthophotos of high accuracy or even cadastral maps, strengthen the reliability and the accuracy of the final outcome, as they depict elements that represent the outline or/and the fragmentation of the cadastral objects.
  - In adverse situation of basemap availability other platforms with lower accuracy can be used, such as UAV images, OSM, etc. These alternatives can assist the registration process but they do not guarantee the accuracy and reliability of the final outcome, especially when it comes to registering property units that are not visible in the available basemap and have complex geometry. To overcome this drawback, the developed technical framework proposes three solutions:
    - (i) the use of geometric tools provided from the mobile application;
    - (ii) the exploitation of the GPS/GNSS sensor of the mobile device, for the outdoor environment;
    - (iii) the establishment of IPS, for the indoor environment where the GPS/GNSS signal is weak.

The research showed that the combined use of all the available 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.

Specifically, for the development of image-analysis and reconstruction techniques, the following conclusions have emerged:

- The exploitation of modern innovative image-analysis techniques can be considered as a good alternative for producing 2D and 3D geospatial basemap, with relatively low financial and computational costs.

- Computer vision technology in combination with low-cost innovative photogrammetric techniques can provide qualitative 2D and 3D information concerning the built environment, that competes the outcome of highly-expensive LiDAR systems. The utilization of 3D point clouds derived from dense matching techniques can be combined with photogrammetry-based methodologies to generate valuable 3D geospatial content for 3D Cadastre.

- The developed methodology for the detection and reconstruction of noisy building roof tops, processes a dense point cloud and classify it into points sets representing: (i) the structural elements of the building roof tops, and (ii) the non-roof tops elements. After the removal of the non-roof elements, proceeds with the imposition of several general constrains referring to the structure and the shape of the buildings. Finally, the reconstruction of the buildings roof tops is achieved through the partial reconstruction of the buildings roof tops structural elements. The outcome of this process can be exploited to provide accurate 3D information regarding the buildings structure or utilized for the complete 3D modelling of the buildings. This information can support the implementation processes of 3D Cadastres and 3D crowdsourced cadastral surveys, in case that the geospatial resources are sufficient. The developed methodology consists a reliable, cost-effective solution for the fast generation of 3D geospatial information or/and 3D models of buildings. Through the visual observation of the 3D reconstruction, the process of identification of the building in which the respective property is located is facilitated. This is significant in densely urbanized areas where the separation and identification of buildings and properties is very difficult by using only a cartographic background (orthophoto, aerial image).

- Deep learning techniques can improve the performance of building detection, playing a critical role in promoting the accuracy of applications of automatic mapping. The developed methodology for buildings detection, extraction and vectorization is based on this finding. It exploits the capabilities of the U-NET++ deep learning algorithm; propose an alternative loss function, aiming to optimize the identification of buildings outlines; and provide an automate extraction and vectorization framework for buildings outlines. To work, a geo-referenced orthophoto of the study area is required as input, while as output it produces the geo-referenced vector outlines of the buildings with satisfactory accuracy. The developed methodology consists a cost-effective solution for the fast generation of a valuable georeferenced vector background, that can be utilized as registration basemap for the implementation of 3D crowdsourced cadastral surveys. However, this particular methodology is best suited to residential or industrial areas with sparsely distributed buildings.

- The data produced through the developed image-analysis methodologies, can be utilized by a wide variety of applications besides 3D Cadastre, such as urban planning, GIS, etc.

8.2.3 Outcome over the technical system

- The developed mobile application is designed appropriately to lead and simplify the registration and 3D modelling procedure. It includes the necessary tools and functionalities for the: (i) visualization of the available 2D and/or 3D geospatial backgrounds; (ii) determination, digitization and automated 3D modelling of the cadastral objects; (iii) generation of the corresponding KML objects; (iv) visualization of the declared cadastral objects in real time, both above and below the ground surface; (v) storage of the geometry, KML representation, descriptive information and relationships between the registered cadastral objects, within a 3D LADM-based online cadastral geodatabase - if an internet connection is available. The generation of the KML representation simplifies the visualization of the registered 3D property models on a variety of different platforms, such as GIS, etc.

- The research showed that in addition to a mobile GIS application, a web GIS application via a desktop computer can also be selected, but prohibiting the user from moving around the property to acquire directly data/measurements. Nevertheless, the increased software and hardware capabilities of a desktop computer combined with the larger screen are the undoubted advantages of this option. However, the choice of the most appropriate capturing tool is always related to the purpose of each application.

- The developed web-based application was focused on the manipulation and registration of BIM data. It includes different functions compared to the mobile application, which offer a better view of both the exterior and interior environment of the BIM. This is achieved through (i) the layer management tool, that allows the user to choose which feature layers to be show or hide, and (ii) the building slicing tool, that allows the user to create a section on the BIM and view the interior environment. To confirm or capture important measurements concerting property metrics, the web application provides a 3D measuring tool that allows the user to measure 3D lengths or areas within the 3D virtual environment. All the numeric and descriptive information are registered through the editor tool to create new or update the current declaration cadastral information into a cadastral online LADM-based database.

- The developed mobile and web applications are easy enough to be learned and used from non-experts. The compilation of the registration process through the applications is affected by three main factors: (i) the volunteer's digital skills, age, perception of geometry matters, (ii) the good operation of the capturing device and especially the screen condition of the mobile device, and (iii) the quality of the internet connection. For the first category of factors, the research indicated that through proper training, online tutorials and real-time assistance, the usage of the mobile application is possible even from elderly people with a moderate relation to smartphones and internet. However, the second and third category of factors refer to unbalanced parameters which cannot be avoided but rarely occur.

- Both applications support processes and operations that allow them to tolerate and manage different data types, and more specifically geometric and parametric structures such as points, lines, planes, surfaces, volumetric objects and BIMs.

- The choice of ESRI product to proceed with the development of the mobile and web applications is only one possible implementation of the developed approach. Other open source platforms can also be used for the development of such software applications.

As for the integration of LADM into 3D crowdsourced cadastral surveys, the following conclusion have emerged:

- Through the integration of LADM standard, a common communication language is established, enhancing the exchangeability of data both between the involved parties within the same country as well as among different countries. Thus, the collected data are characterized by completeness as they are appropriately attributed, distinguished and related by logical rules and maintain the corresponding time stamp regarding the time period of their capture. This, allows the timeless monitoring of the collected crowdsourced data.

- The research showed that until now the LADM lacks of a connection with widely known spatial models, such as BIM; and, does not define the acceptable 3D geometries and representations for the 3D cadastral objects, consisting still an active research subject.

- Another 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. 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. 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.

- The future world of smart cities needs proprietary BIMs as a clarifying tool, providing a clearer picture with relation to property RRRs. While BIM may be used to provide the geometry of the complex physical buildings' spaces for 3D Cadastre, it should also be connected with a legal model and especially LADM. The establishment of this linkage can provide a better understanding regarding the spatial extent of the legal RRRs, ensuring clarity to legal issues and avoiding improper behaviors and disputes between the stakeholders.

- The developed database schema proposes an alternative extent to the current structure of LADM conceptual schema, including: (i) a simple description of the geometric representation of the cadastral objects, as polygonal objects (open or closed), and (ii) a potential linkage between LADM and BIM/IFC standards, focusing on the connection of the legal spaces defined in BIM through the IFC standard and specifically through the IfcSpace entity. This connection concerns only the legal spaces defined in BIM, assuming that they are corrected delimited. The establishment of a more solid connection between LADM and BIM including also the physical counterparts of BIM and the identification of the different types of legal objects was out of the scope of this study.

- The developed framework results in the generation of an up-to-date 3D cadastral database, which may be further processed by the cadastral agency in order to proceed with the necessary evaluation and control of the submitted data.

- Exploiting the capabilities of a web server to store and maintain the collected geospatial data is significant. It allows the immediate import of new records, the updating of existing records in real time, and facilitates their management from remote environments. The development and maintenance of such a platform has several benefits for the efficient and sustainable management of the land, real estates and a variety of other services.

8.2.4 Outcome over the data quality

- In order to be able to evaluate and criticize the quality of a crowdsourced project, we should first consider the purpose of its implementation. For this particular research the fundamental question that need to be addressed in order to evaluate the quality of the crowdsourced data is: "*Is the achieved quality adequate according to the purpose for which the data are collected?*" The answer to this question is that safeguarding the property RRRs is imperative even if the achieved accuracy does not satisfy the high precision specifications of the current 2D land registers. A fast, reliable but not highly accurate solution can be a starting point for the initial collection of cadastral information, which accuracy may be improved at a later stage of the cadastral procedures.

- It should be noted that most cadastral systems, even some long existing cadastral systems in developed countries, may need to improve their geometric accuracies in some parts of their jurisdiction. The most common reason is that long existing systems do not usually have a unified geometric accuracy, as parts of the country were surveyed at different periods and most of the cadastral diagrams were digitized from existing analog maps.

- Using the current tools, such as UAVs, right holders participation and mobile applications, it is possible to gradually improve the accuracy as well as completeness -if and where needed- in a fast and affordable manner. Also, maintenance of the systems may be achieved more easily in future by using such tools. This may require some legal amendments, especially if restrictions in using the cloud are in place. However, this is not the case for many countries.

- The developed framework follows a fit-for-purpose approach, good enough for managing current land issues within a specific country or region at an affordable cost, rather than simply following advanced technical standards. The quality check of the data may be conducted by a NCMA, which, in this case, can operate as a gatekeeper of the crowdsourced 3D data.

- The research showed that the developed technical solution can provide results of satisfactory accuracy, e.g., with an average deviation of 0.20 m. Even in adverse cases of basemap availability, the developed solution provide result with an average accuracy of 0.50 m. The achieved accuracy may seem insufficient but it should be noted that it may meet the accuracy specifications of several countries, as Greece, where the current accuracy specifications of the Greek Cadastre for urban areas is 0.71 m (RMSExy).

- The developed parametric modelling algorithm can provide reliable results exploiting the input data, concerning: (ii) the digitized polygon referring to the declared cadastral object (land parcel or property unit), and (ii) the numeric information regarding the height of the declared property – when needed. An important parameter for this process to be successfully fulfilled is the quality of the utilized DTM. A relatively low-quality DTM may lead to some small shape defects, while this may be avoided with the utilization of a highly accurate DTM. However, for the purpose of this research the use of the freely available DTM of ESRI was led to satisfactory results, even including some – rarely occurred – altitude irregularities ("altitude jumps").

- It is noted that although the final model appears in its correct position horizontally, some ambiguities regarding its vertical alignment remain. This is mainly due to the used DTM, which in our study area appears at a higher altitude than in the real world. The result of this mismatch is that the ground floor of the building appears to be below the surface of the ground. However, this problem can be solved by using a more up-to-date and accurate DTM. Nevertheless, the final result is satisfactory for the purpose of this research.

- As the data were collected by non-professionals and with low-cost equipment the existence of some gross errors is inevitable. However, all these weaknesses should be identified and corrected through the control stage by professional surveyors, informing right holders to take appropriate actions to correct them.

- The use of the mobile application directly by professionals leveraging the knowledge of the right holders can lead to a further reduction of errors and therefore of the necessary controls.

- Finding the balance in which citizens wish to collect and contribute data through a relatively simple procedure in a way that quality of the data does not deteriorate.

8.3 Future Research

In addition to the topics covered in this dissertation, there are several aspects that can be further investigated. In this last section, some thoughts and ideas for future research are discussed. The main issues that may be considered for the next step of this research include:

- A larger scale implementation of the proposed technical framework aiming the detection and correction of potential weaknesses that may occur in wide range applications, such as at city level.

- The implementation of practical experiments using the 2D or/and 3D outcome of the developed image-analysis methodologies as cadastral registration backgrounds, to conclude about their potentials for this process.
- The investigation of the potential controls on the collected data in order to reduce the manual interference in the control process and automate the procedure.
- The investigation of integrating the developed mobile cadastral application with a Bluetooth-based IPS, similar to the one explored in this dissertation; the practical application of the optimized system for Indoor cadastral surveys; and, the exploration of signals from technologies other than Bluetooth, such as wifi, etc., or the simultaneous processing of signals by heterogeneous sensors (e.g., Bluetooth and WiFi signals) to increase the accuracy of Indoor cadastral mapping.
- The further investigation of 3D reconstruction algorithms, methods and techniques, for the exploitation of images taken by smartphones for the automatic generation 3D building/property models able to support 3D crowdsourced cadastral surveys.
- The development of a conceptual scheme for the establishment of an integrated link between the legal model of LADM and the IFC standard, in order the exploitation of BIM technology in the implementation of the 3D cadastre to become feasible in official basis. Within this framework, it is also very interesting to explore and establish a common framework for defining the position of legal boundaries.

Another issue that can be explored is the use of alternative platforms for the development of cadastral mobile application software. Utilizing ESRI tools is an initial choice but not unique. The use of other 3D geospatial platforms, such as Cesium (Cesium, 2022), consist a good alternative that can be investigated at a later stage.

Finally, although this dissertation focuses on the 3D cadastre, the utilization of the developed algorithms, methodologies and software can be used to support a wider range of applications related to both 2D & 3D geospatial information acquisition, 3D modeling and change detection. The adaptation and extension of the developed technical framework to another application area is of great interest. Other areas of application that can be explored include DTs, risk management, urban planning, GIS, etc.

References

Adad, M. A., Semlali, E. H. & Ibannain, F. (2019). Comprehensive Ontology Model of Moroccan Land Administration Domain Applied to the National Land Governance. In: *Geospatial Technologies for Effective Land Governance,* pp. 28-47. IGI Global.

Adad, M. A., Semlali, E. H., El-Ayachi, M. & Ibannain, F. (2020). Supporting land data integration and standardization through the LADM standard: Case of Morocco's country profile MA-LADM. *Land Use Policy*, 97, 104762.

Adlington, G. (2011). The rise or fall of the cadastre empire. In: *International FIG Symposium & Commission 7 Annual Meeting 'Cadastre*, 2, 21-28.

Al-Bakri, M. & Fairbairn, D. (2010). Assessing the Accuracy of 'Crowdsourced' Data and its Integration with Official Spatial Data Sets. In: *N.J. Tate and P.F. Fisher, eds. Proceedings of the ninth International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences*, 20–23 July, Leicester, pp. 317–320.

Alattas, A., Zlatanova, S., Van Oosterom, P., Chatzinikolaou, E., Lemmen, C. & Li, K. J. (2017). Supporting indoor navigation using access rights to spaces based on combined use of IndoorGML and LADM models. *ISPRS International Journal of Geo-Information,* 6(12):384. https://doi.org/10.3390/ijgi6120384

Alattas, A., van Oosterom, P. & Zlatanova, S. (2018a). Deriving the technical model for the indoor navigation prototype based on the integration of IndoorGML and LADM conceptual model. In: *7th International FIG Workshop on the Land Administration Domain Model,* Zagreb, Croatia, pp. 245-267.

Alattas, A., van Oosterom, P., Zlatanova, S., Diakité, A. A. & Yan, J. (2018b). Developing a database for the LADM-IndoorGML model. In: *6th International FIG 3D Cadastre Workshop*, pp. 261-278.

Alattas, A., van Oosterom, P., Zlatanova, S., Hoeneveld, D. & Verbree, E. (2018c). Using the combined LADM-IndoorGML model to support buiilding evacuation. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42(4):11-23.

Alattas, A., van Oosterom, P. & Zlatanova, S. (2019). Initial Country Profile of the Kingdom of Saudi Arabia based on LADM. In: *8th Land Administration Domain Model Workshop (LADM 2019),* 11 p.

Alattas, A., Kalogianni, E., Alzahrani, T., Zlatanova, S. & van Oosterom, P. (2021). Mapping private, common, and exclusive common spaces in buildings from BIM/IFC to LADM. A case study from Saudi Arabia. *Land Use Policy*, 104, 105355.

Alexa, M., Behr, J., Cohen-Or, D., Fleishman, S., Levin, D. & Silva, C. T. (2003). Computing and rendering point set surfaces. *IEEE Transactions on visualization and computer graphics*, *9*(1):3-15.

Alidoost, F. & Arefi, H. (2016). Knowledge based 3D building model recognition using convolutional neural networks from lidar and aerial imageries. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLI-B3, pp. 833-840.

Amenta, N., Choi, S. & Kolluri, R. (2001). The Power Crust. In: *6th ACM symposium on Solid modeling and applications*, pp. 249-266.

Ammar, R.K. & Neeraj, D. (2013). SLRB Bahrain – 3D Property Registration System. *In: 5th Land Administration Domain Model Workshop,* Kuala Lumpur, pp. 419-432.

Apostolopoulos, K., Geli, M., Petrelli, P., Potsiou, C. & Ioannidis, C. (2018). A new model for cadastral surveying using crowdsourcing. *Survey review*, *50*(359):122-133.

Atazadeh, B., Rajabifard, A. & Kalantari, M. (2018). Connecting LADM and IFC Standards—Pathways towards an Integrated Legal-Physical Model. In: *7th International FIG Workshop on the Land Administration Domain Model*, Zagreb, Croatia, 12–13 April 2018, pp. 89-102.

Atazadeh, B., Rajabifard, A., Zhang, Y. & Barzegar, M. (2019). Querying 3D cadastral information from BIM models. *ISPRS International Journal of Geo-Information*, *8*(8), 329. https://doi.org/10.3390/ijgi8080329

Atazadeh, B., Olfat, H., Rajabifard, A., Kalantari, M., Shojaei, D. & Marjani, A. M. (2021). Linking Land Administration Domain Model and BIM environment for 3D digital cadastre in multi-storey buildings. *Land Use Policy*, 104, 105367. https://doi.org/10.1016/j.landusepol.2021.105367

Awrangjeb, M., Zhang, C. & Fraser, C. S. (2012). Automatic reconstruction of building roofs through effective integration of LiDAR and multispectral imagery. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, I-3, 203–208, https://doi.org/10.5194/isprsannals-I-3-203-2012

Badrinarayanan, V., Kendall, A. & Cipolla, R. (2017). Segnet: A deep convolutional encoder-decoder architecture for image segmentation. *IEEE transactions on pattern analysis and machine intelligence*, *39*(12):2481-2495.

Barzegar, M., Rajabifard, A., Kalantari, M. & Atazadeh, B. (2021). An IFC-based database schema for mapping BIM data into a 3D spatially enabled land administration database. *International Journal of Digital Earth*, *14*(6):736-765. DOI: 10.1080/17538947.2021.1875062.

Basiouka, S. (2015). *The Volunteered Geographic Information in Land Administration: Crowdsourcing Techniques in Cadastral Surveys*. Doctoral Dissertation, National Technical University of Athens, Greece.

Basiouka, S. & Potsiou, C. (2012a). VGI in Cadastre: A Greek experiment to investigate the potential of crowd sourcing techniques in Cadastral Mapping. *Survey Review*, *44*(325):153-161.

Basiouka, S., & Potsiou, C. (2012b). Improving cadastral survey procedures using crowd sourcing technique. *Coordinates magazine*, *8*(10):20-26.

Basiouka, S. & Potsiou, C. (2014). The volunteered geographic information in cadastre: perspectives and citizens' motivations over potential participation in mapping. *GeoJournal*, *79*(3):343-355.

Becker, S. & Haala, N. (2009). Grammar supported facade reconstruction from mobile lidar mapping. In: *ISPRS Workshop, CMRT09-City Models, Roads and Traffic*, XXXVIII/3-W4, 13 p. https://www.isprs.org/proceedings/xxxviii/3-w4/pub/CMRT09_229.pdf

Benhamu, M. (2006). A GIS-related multi layers 3D cadastre in Israel. In: *XXIII FIG Congress,* Munich, Germany, 12 p.

https://www.fig.net/resources/proceedings/fig_proceedings/fig2006/papers/ts14/ts14_04_benhamu_0581.pdf

Benhamu, M. & Doytsher, Y. (2003). Toward a spatial 3D cadastre in Israel. *Computers, Environment and Urban Systems*, *27*(4):359-374.

Benhamu, M. & Doytsher, Y. (2001). Research toward a multilayer 3-D cadastre: interim results. In: *International workshop on "3D Cadastres", Registration of properties in strata,* Delft, The Netherlands, pp. 35-51. https://www.fig.net/resources/proceedings/2001/2001_3dcadastre/3Dcad_2001_10.pdf.pdf

Bernardini, F., Mittleman, J., Rushmeier, H., Silva, C. & Taubin, G. (1999). The ball-pivoting algorithm for surface reconstruction. *IEEE transactions on visualization and computer graphics*, *5*(4):349-359.

Bernardini, F., Rushmeier, H., Martin, I. M., Mittleman, J. & Taubin, G. (2002). Building a digital model of Michelangelo's Florentine Pieta. *IEEE Computer Graphics and Applications*, *22*(1):59-67.

Beraldin, J. A., Picard, M., El-Hakim, S. F., Godin, G., Valzano, V. & Bandiera, A. (2005, January). Combining 3D technologies for cultural heritage interpretation and entertainment. In: *Videometrics VIII*, Vol. 5665, pp. 108-118. SPIE.

Biljecki, F., Kumar, K. & Nagel, C. (2018). CityGML application domain extension (ADE): overview of developments. *Open Geospatial Data, Software and Standards,* 3(1):1-17.

Blais, F. (2004). Review of 20 years of range sensor development. *Journal of electronic imaging*, *13*(1):231-243.

Boissonnat, J. D. & Oudot, S. (2005). Provably good sampling and meshing of surfaces. *Graphical Models*, *67*(5):405-451.

Bokhovkin, A. & Burnaev, E. (2019). Boundary loss for remote sensing imagery semantic segmentation. In: *Lu, H., Tang, H., Wang, Z. (eds) Advances in Neural Networks – ISNN 2019. ISNN 2019. Lecture Notes in Computer Science,* vol 11555. Springer, Cham. https://doi.org/10.1007/978-3-030-22808-8_38

Borg, C. E. & Cannataci, J. A. (2002). Thealasermetry: a hybrid approach to documentation of sites and artefacts. In: *CIPA-ISPRS Workshop on Scanning for Cultural Heritage*, pp. 93-104.

Borrmann, A., Konig, M., Koch, C. & Beetz, J. (2018). Building Information Modeling. *Springer International Publishing,* 584. doi: 10.1007/978-3-319-92862-3.

Brenner, C. (2005). Building reconstruction from images and laser scanning. *International Journal of Applied Earth Observation and Geoinformation*, *6*(3-4):187-198.

Brown, G. & Kyttä, M. (2014). Key issues and research priorities for public participation GIS (PPGIS): A synthesis based on empirical research. *Applied geography*, *46*:122-136.

Bshouty, E., Shafir, A. & Dalyot, S. (2020). Towards the generation of 3D OpenStreetMap building models from single contributed photographs. *Computers, Environment and Urban Systems*, *79,* 101421.

BuildingSmart, 2022. *Building Smart*. https://www.buildingsmart.org/ (Accessed January 2022).

Burges, C. J. (1998). A tutorial on support vector machines for pattern recognition. *Data mining and knowledge discovery*, *2*(2):121-167.

Çağdaş, V., Stubkjær, E., de Vries, W. T., Van der Merwe, C., Paasch, J. M., Paulsson, J., Schwery, N., Ploeger, H., Isikdag, U. & Kara, A. (2018). Co-ownership shares in condominiums–A comparison across jurisdictions and standards: Long version. In: *6th International FIG 3D Cadastre Workshop*, 2-4 October 2018, Delft, The Netherlands.

Canny, J. (1986). A computational approach to edge detection. *IEEE Transactions on pattern analysis and machine intelligence*, 6:679-698.

Cetl, V., Ioannidis, C., Dalyot, S., Doytsher, Y., Felus, Y., Haklay, M., Mueller, H., Potsiou, C., Rispoli, E. & Siriba, D. (2019). New Trends in Geospatial Information: The Land Surveyors Role in the Era of Crowdsourcing and VGI. *FIG Publication No 73*, International Federation of Surveyors (FIG).

CGAL. (2019). *Polyhedral surfaces.* https://doc.cgal.org/latest/Polyhedron/index.html (Accessed March 2019).

Chhor, G., Aramburu, C. B. & Bougdal-Lambert, I. (2017). Satellite image segmentation for building detection using U-Net. http://cs229.stanford.edu/proj2017/final-reports/5243715.pdf

Chiang, H.C. (2012). Data Modelling and Application of 3D Cadastre in Taiwan. In: *3rd International Workshop on 3D Cadastres: Developments and Practices*, Shenzhen, China, pp. 137-157.

Clouston, A. (2015). *Crowdsourcing the Cadastre: The Applicability of Crowdsourced Geospatial Information to the New Zealand Cadastre*. Masters thesis, Victoria University of Wellington, New Zealand.http://researcharchive.vuw.ac.nz/xmlui/bitstream/handle/10063/4234/thesis.pdf?sequence=2.

CodePen. (2021). Web development environment. https://codepen.io/ (Accessed January 2021).

Cohen, L. D. (1991). On active contour models and balloons. *CVGIP: Image understanding*, *53*(2):211-218.

Coleman, D. J. (2010). Volunteered geographic information in spatial data infrastructure: An early look at opportunities and constraints. In: *GSDI 12 world conference*, pp. 131-147.

Coleman, D., Georgiadou, Y. & Labonte, J. (2009). Volunteered geographic information: The nature and motivation of produsers. *International Journal of Spatial Data Infrastructures Research*, *4*(4):332-358.

CSDILA. (2019). *Victorian 3D Digital Cadastre Roadmap*. Centre for SDIs and Land Administration (CSDILA) of the University of Melbourne, Melbourne, Australia.

Csurka, G., Larlus, D., Perronnin, F. & Meylan, F. (2004). What is a good evaluation measure for semantic segmentation? *IEEE Trans. Pattern Anal. Mach. Intell (PAMI)*, *26*(1).

Dal Poz, A. P. & Fernandes, V. J. M. (2016). Extraction of roof lines from high-resolution images by a grouping method. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B3, pp. 853–857, https://doi.org/10.5194/isprs-archives-XLI-B3-853-2016

Dawidowicz, A. & Źróbek, R. (2017). Land administration system for sustainable development–case study of Poland. *Real Estate Management and Valuation*, 25(1):112-122.

de Vries, W. T., Bennett, R. M. & Zevenbergen, J. A. (2015). Neo-cadastres: innovative solution for land users without state based land rights, or just reflections of institutional isomorphism? *Survey Review*, *47*(342):220-229.

Dimopoulou, E. 2015. *ND Cadastre*. Hellenic Academic Libraries Link (in Greek).

Dimopoulou, E., Karki, S., Miodrag, R., Almeida, J.P.D., Griffith-Charles, C., Thompson, R., Ying, S. & Oosterom, P. (2018). Initial registration of 3D parcels. *In: 5th International FIG 3D Cadastre Workshop,* Athens, Greece, pp. 105-132.

Döner, F. (2021). Analysis of literature on 3D cadastre. *International Journal of Engineering and Geosciences*, *6*(2):90-97.

Douglas, D. H. & Peucker, T. K. (1973). Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *Cartographica: The international journal for geographic information and geovisualization*, *10*(2):112-122.

Eaglin, T., Subramanian, K. & Payton, J. (2013). 3D modeling by the masses: A mobile app for modeling buildings. In: *2013 IEEE international conference on pervasive computing and communications workshops (PERCOM workshops)*, pp. 315-317.

Eigen. (2018). *Eigen: C++ template library for linear algebra* http://eigen.tuxfamily.org/index.php?title=Main_Page (Accessed March 2018).

El-Hakim, S. F., Beraldin, J. A., Picard, M. & Godin, G. (2004). Detailed 3D reconstruction of large-scale heritage sites with integrated techniques. *IEEE computer graphics and applications*, *24*(3):21-29.

Elgan, M. (2022). Kinect: Microsoft's accidental success story. https://www.computerworld.com/article/2509127/kinect--microsoft-s-accidental-success-story.html (Accessed April 2022).

Ellul, C., de Almeida, J.P. & Romano, R. (2016). Does coimbra need a 3d cadastre? Prototyping a crowdsourcing app as a first step to finding out. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci*., IV-2/W1, pp. 55-62. doi.org/10.5194/isprs-annals-IV-2-W1-55-2016.

Enemark, S., Bell, K., Lemmen, C. & McLaren, R. (2014). Building fit-for-purpose land administration systems. In: *XXV FIG international congress*, pp. 16-21.

EOS_RTK_GNSS. (2020). *EOS Arrow Gold RTK GNSS receiver with SafeRTK*. https://eos-gnss.com/product/arrow-series/arrow-gold (Accessed March 2020).

ESRI. (2022). *ArcGIS online application*. http://www.esri.com/software/arcgis/arcgisonline (Accessed August 2022).

Fan, H. & Zipf, A. (2016). Modelling the world in 3D from VGI/Crowdsourced data. *In: Capineri, C, Haklay, M, Huang, H, Antoniou, V, Kettunen, J, Ostermann, F and Purves, R. (eds.) European Handbook of Crowdsourced Geographic Information*, pp. 435–446, London: Ubiquity Press.

FAO. (2011). *FAO FLOSS SOLA Data Dictionary for the SOLA Desktop Development Snapshot*, version 1.0 (Prepared by Elton Manoku, Matthew Boafo and Neil Pullar. Version 1.0, August 24, 2011).

Fernandez-Moral, E., Martins, R., Wolf, D. & Rives, P. (2018). A new metric for evaluating semantic segmentation: leveraging global and contour accuracy. In: *2018 IEEE Intelligent Vehicles Symposium (IV)*, Changshu, China, pp. 1051-1056. doi: 10.1109/IVS.2018.8500497

Fischler, M. A. & Bolles, R. C. (1981). Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM*, *24*(6):381-395.

Flack, P. A., Willmott, J., Browne, S. P., Arnold, D. B. & Day, A. M. (2001). Scene assembly for large scale urban reconstructions. In: *2001 Conference on Virtual reality, archeology, and cultural heritage*, pp. 227-234.

Foody, G. M., Mooney, P., See, L., Kerle, N., Olteanu-Raimond, A. M. & Fonte, C. (2015). *Current status and future trends in crowd-sourcing geographic information*. Working Paper of COST Action TD1202, University of Nottingham, 6 p.

Foody, G. M., See, L., Fritz, S., Van der Velde, M., Perger, C., Schill, C., Schill C., Boyd, D.S. & Comber, A. (2015). Accurate attribute mapping from volunteered geographic information: issues of volunteer quantity and quality. *The Cartographic Journal*, *52*(4):336-344.

Furukawa, Y. & Hernández, C. (2015). Multi-view stereo: A tutorial. *Foundations and Trends® in Computer Graphics and Vision*, *9*(1-2):1-148.

Furukawa, Y. & Ponce, J. (2007, July). Accurate, dense, and robust multi-view stereopsis (pmvs). In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, 32(8):1362–1376.

Furukawa, Y. & Ponce, J. (2009). Accurate, dense, and robust multi-view stereopsis. *IEEE transactions on pattern analysis and machine intelligence*, *32*(8):1362-1376.

García, J. M. O., Soriano, L. I. V. & Martín-Varés, A. V. (2011). 3D modeling and representation of the Spanish Cadastral cartography. In: *2nd International workshop on 3D cadastres*, Delft, pp. 209-222. https://www.fig.net/resources/proceedings/2011/2011_3dcadastre/3Dcad_2011_23.pdf

Gkeli, M., Apostolopoulos, K., Mourafetis, G., Ioannidis, C. & Potsiou, C. (2016). Crowdsourcing and mobile services for a fit-for-purpose Cadastre in Greece. *In: Fourth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2016), SPIE*, 9688:17. doi:10.1117/12.2240835.

Goetz, M. & Zipf, A. (2012). Towards defining a framework for the automatic derivation of 3D CityGML models from volunteered geographic information. *International Journal of 3-D Information Modeling (IJ3DIM)*, *1*(2):1-16.

Goodchild, M. F. (2007a). Citizens as sensors: the world of volunteered geography. *GeoJournal*, *69*(4):211-221.

Goodchild, M. F. (2007b). Citizens as voluntary sensors: spatial data infrastructure in the world of Web 2.0. *International journal of spatial data infrastructures research*, *2*(2):24-32.

Goodchild, M. F. & Li, L. (2012). Assuring the quality of volunteered geographic information. *Spatial statistics*, *1*:110-120.

Góźdź, K. & Pachelski, W. (2014). The LADM as a core for developing three-dimensional cadastral data model for Poland. In: *14th International Multidisciplinary Scientific GeoConference SGEM 2014*, pp. 841-848.

Góźdź, K. J. & Van Oosterom, P. J. M. (2016). Developing the information infrastructure based on LADM–the case of Poland. *Survey review*, *48*(348):168-180.

Gröger, G., Kolbe, T. H., Czerwinski, A. & Nagel, C. (2008). *OpenGIS® City Geography Markup Language (CityGML) Implementation Specification*. Version, 1(0), 08-007.

Gröger, G. & Plümer, L. (2012). CityGML–Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, *71*:12-33.

Groger, G., Kolbe, T., Nagel, C. & Hafele, K.H.(2012). *OGC City Geography Markup Language (CityGML) En-Coding Standard*. Open Geospatial Consort. Wayland, MA, USA.

Gruen, A. & Li, H. (1997). Semi-automatic linear feature extraction by dynamic programming and LSB-snakes. *Photogrammetric engineering and remote sensing*, *63*(8):985-994.

Grun, A. (2000). Semi-automated approaches to site recording and modelling. *International Archives of Photogrammetry and Remote Sensing,* 33(5/1):309–318.

Guler, D. & Yomralioglu, T. (2021). A conceptual model for IFC-based delineation of condominium rights in turkey: initial experiments. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, VIII-4/W2-2021, pp. 5–12.

Guler, D. & Yomralioglu, T. (2022). Reviewing the literature on the tripartite cycle containing digital building permit, 3D city modeling, and 3D property ownership. *Land Use Policy*. 121:106337.

Gulliver, T. (2015). *Developing a 3D Digital Cadastral System for New Zealand*. Master's Thesis, Department of Geography, University of Canterbury, Christchurch, New Zealand.

Guo, R., Luo, F., Zhao, Z., He, B., Li, L., Luo, P. & Ying, S. (2014). The applications and practices of 3D cadastre in Shenzhen. In: *4th International Workshop on 3D Cadastres,* 9-11 November 2014, Dubai, United Arab Emirates, pp. 299-312.

Guo, R., Li, L., Ying, S., Luo, P., He, B. & Jiang, R. (2013). Developing a 3D cadastre for the administration of urban land use: A case study of Shenzhen, China. *Computers, Environment and Urban Systems*, *40*:46-55.

Guo, R., Li, L., He, B., Luo, P., Ying, S., Zhao, Z. & Jiang, R. (2011). 3D cadastre in China: A case study in Shenzhen City. In: *2nd International Workshop on 3D Cadastres*, Delft, The Netherlands, 16-18 November, pp. 291-310. https://www.fig.net/resources/proceedings/2011/2011_3dcadastre/3Dcad_2011_28.pdf

Gürsoy Sürmeneli, H., Alkan, M. & Koeva, M. (2022a). Design and implementation of a 4D cadastral legal model for Turkish land administration infrastructure based on LADM. In: *Geocarto International,* 37:26, 12096-12118, DOI: 10.1080/10106049.2022.2063410

Gürsoy Sürmeneli, H., Koeva, M. & Alkan, M. (2022b). The Application Domain Extension (ADE) 4D cadastral data model and its application in Turkey. *Land*, 11(5), 634.

Haala, N. (2011). Multiray photogrammetry and dense image matching. In: *Photogrammetric week*, VDE Verlag, 11, pp. 185-195.

Haala, N. & Kada, M. (2010). An update on automatic 3D building reconstruction. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(6):570-580.

Haasdyk, J & Roberts, C. (2013). Monitoring Station Movement using a State-Wide Simultaneous. In: *International Global Navigation Satellite Systems Society IGNSS Symposium 2013*, Outrigger Gold Coast, Queensland, Australia.

Haklay, M. (2010). How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environment and planning B: Planning and design*, *37*(4):682-703.

Haklay, M., Basiouka, S., Antoniou, V. & Ather, A. (2010). How many volunteers does it take to map an area well? The validity of Linus' law to volunteered geographic information. *The cartographic journal*, *47*(4):315-322.

Haklay, M. & Tobón, C. (2003). Usability evaluation and PPGIS: towards a user-centred design approach. *International Journal of Geographical Information Science*, *17*(6):577-592.

Hartley, R., & Zisserman, A. (2003). *Multiple view geometry in computer vision*. Cambridge University Press.

Hartmann, W., Havlena, M. & Schindler, K. (2016). Towards complete, geo-referenced 3d models from crowd-sourced amateur images. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, III-3:51-58.

Havlena, M. & Schindler, K. (2014). Vocmatch: Efficient multiview correspondence for structure from motion. In: *European Conference on Computer Vision*, pp. 46-60. Springer, Cham.

He, K., Zhang, X., Ren, S. & Sun, J. (2016). Deep residual learning for image recognition. In: *IEEE conference on computer vision and pattern recognition*, pp. 770-778.

Helbich, M., Amelunxen, C., Neis, P. & Zipf, A. (2010). Investigations on locational accuracy of volunteered geographic information using OpenStreetMap data. In: *GIScience 2010 Workshop*, Zurich, Switzerland, pp. 14-17.

HellenicCadastre. 2022. *The Cadastral project in Greece*. https://www.ktimatologio.gr/en (Accessed February 2022).

Hirschmuller, H. (2005). Accurate and efficient stereo processing by semi-global matching and mutual information. In: *2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05)*, Vol. 2, pp. 807-814.

Hirschmuller, H. (2007). Stereo processing by semiglobal matching and mutual information. *IEEE Transactions on pattern analysis and machine intelligence*, *30*(2):328-341.

Hirschmüller, H. (2011). Semi-global matching-motivation, developments and applications. In: *Photogrammetric Week 11*, pp. 173-184.

Hirschmüller, H., Buder, M. & Ernst, I. (2012). Memory efficient semi-global matching. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, I-3, 371–376. https://doi.org/10.5194/isprsannals-I-3-371-2012

Hirschmuller, H. & Scharstein, D. (2007). Evaluation of cost functions for stereo matching. In: *2007 IEEE Conference on Computer Vision and Pattern Recognition*, Minneapolis, MN, USA, pp. 1-8. doi: 10.1109/CVPR.2007.383248

Hirschmuller, H. & Scharstein, D. (2008). Evaluation of stereo matching costs on images with radiometric differences. *IEEE transactions on pattern analysis and machine intelligence*, *31*(9):1582-1599.

Hornung, A. & Kobbelt, L. (2006, June). Robust reconstruction of watertight 3 d models from non-uniformly sampled point clouds without normal information. In: *Eurographics Symposium on Geometry Processing*, pp. 41-50. https://www.graphics.rwth-aachen.de/media/papers/hornung2006sgp_051.pdf

Hristova, D., Mashhadi, A., Quattrone, G. & Capra, L. (2012). Mapping community engagement with urban crowd-sourcing. In: *International AAAI Conference on Web and Social Media*, 6(5):14-19.

INSPIRE. (2009). D2. 8. I. 6 *INSPIRE Data Specification on Cadastral Parcels—Guidelines*.

Ioannou, Y., Taati, B., Harrap, R. & Greenspan, M. (2012). Difference of normals as a multi-scale operator in unorganized point clouds. In: *2012 Second International Conference on 3D Imaging, Modeling, Processing, Visualization & Transmission*, pp. 501-508. IEEE.

ISO, I. (2008). *ISO 19107-Geographic information--Spatial schema*.

ISO, I. (2012). *19152: 2012 Geographic Information—Land Administration Domain Model (LADM)*. Geneva, Switzerland.

Jaljolie, R., van Oosterom, P. & Dalyot, S. (2016). Systematic analysis of functionalities for the Israeli 3D cadastre. In: *5th International FIG Workshop on 3D Cadastres*. International Federation of Surveyors (FIG), Athens, Greece, pp. 447-472.

Jeon, B. K., Jang, J. H. & Hong, K. S. (2002). Road detection in spaceborne SAR images using a genetic algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, *40*(1):22-29.

Jeong, J. & Kim, T. (2016). Semi-automatic building models and façade texture mapping from mobile phone images. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, 613.

Jones, B., Lemmen, C. H. J. & Molendijk, M. (2017). Low Cost, Post Conflict Cadastre with Modern Technology. In: *Annual World Bank Conference on Land and Poverty,* The World Bank. *Washington, D.C. March 20-24, 2017*. https://www.conftool.com/landandpoverty2017/index.php?page=browseSessions&form_session=35&mode=list&presentations=show.

Kada, M. (2009). The 3D Berlin project. In: *Fritsch, D. (Ed.), Photogrammetric Week 2009*. Wichmann Verlag, Heidelberg, pp. 331–340.

Kada, M. & McKinley, L. (2009). 3D building reconstruction from LiDAR based on a cell decomposition approach. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* II-3/W4, pp. 157-164.

Kaggle (2022). Kaggle: An online community platform for data scientists and machine learning enthusiasts https://www.kaggle.com/ (Accessed March 2022).

Kalogianni, E. (2015). *Design of a 3D multipurpose land administrative system for Greece in the context of LADM*. Master Thesis, National Technical University of Athens.

Karantzalos, K. & Argialas, D. (2009). A region-based level set segmentation for automatic detection of man-made objects from aerial and satellite images. *Photogrammetric Engineering & Remote Sensing*, *75*(6):667-677.

Karantzalos, K. & Paragios, N. (2010). Large-scale building reconstruction through information fusion and 3-d priors. *IEEE Transactions on Geoscience and Remote Sensing*, *48*(5):2283-2296.

Karki, S. (2013). *3D cadastre implementation issues in Australia*. Doctoral dissertation, University of Southern Queensland.

Kass, M., Witkin, A. & Terzopoulos, D. (1988). Snakes: Active contour models. *International journal of computer vision*, *1*(4):321-331.

Kabolizade, M., Ebadi, H. & Ahmadi, S. (2010). An improved snake model for automatic extraction of buildings from urban aerial images and LiDAR data. *Computers, Environment and Urban Systems*, *34*(5):435-441.

Kazhdan, M., Bolitho, M. & Hoppe, H. (2006). Poisson surface reconstruction. In: *4th Eurographics Symposium on Geometry processing* (Vol. 7).

Kazhdan, M., & Hoppe, H. (2013). Screened poisson surface reconstruction. *ACM Transactions on Graphics (ToG)*, *32*(3):1-13.

Kendzi. (2022). 3D plug-in for JOSM. http://wiki.openstreetmap.org/wiki/Kendzi3d (Accessed April 2022).

Keenja, E., De Vries, W. T., Bennett, R. M. & Laarakker, P. (2012). Crowd sourcing for land administration: Perceptions within Netherlands Kadaster. In: *FIG Working Week 2012 - Knowing to manage the territory, protect the environment, evaluate the cultural heritage*, Rome, 6-10 May, 12 p.

Kingma, D. P. & Ba, J. (2014). Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*.

Kitsakis, D. O. (2020). *Legal requirements for real property stratification*. Doctoral Dissertation, National Technical University of Athens, Greece.

Kitsakis, D., Apostolou, C. & Dimopoulou, E. (2018). Three-dimensional cadastre modelling of customary real property rights. *Survey review*, 50(359):107-121.

Kitsakis, D. & Dimopoulou, E. (2014). 3D cadastres: legal approaches and necessary reforms. *Survey review*, *46*(338):322-332.

Koeva, M., Nikoohemat, S., Oude Elberink, S., Morales, J., Lemmen, C. & Zevenbergen, J. (2019). Towards 3D Indoor Cadastre Based on Change Detection from Point Clouds. *Remote sensing*, *11*(17), 1972.

Köhn, A., Tian, J. & Kurz, F. (2016). Automatic Building Extraction and Roof Reconstruction in 3k Imagery Based on Line Segments. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B3, pp. 625–631. https://doi.org/10.5194/isprs-archives-XLI-B3-625-2016

Kolluri, R., Shewchuk, J. R. & O'Brien, J. F. (2004). Spectral surface reconstruction from noisy point clouds. In: *Proceedings of the 2004 Eurographics/ACM SIGGRAPH symposium on Geometry processing*, pp. 11-21.

Kutzner, T. & Kolbe, T. H. (2018). CityGML 3.0: sneak preview. In: *PFGK18-Photogrammetrie-Fernerkundung-Geoinformatik-Kartographie, 37.* pp. 835-839.

Laarakker, P. M. & de Vries, W. T. (2011). www. opencadastre. org: exploring potential avenues and concerns. In: *FIG working week 2011 Bridging the gap between cultures: technical programme and proceedings*, Marrakech, Morocco, 18-22 May 2011, 16 p.

Labatut, P., Pons, J. P. & Keriven, R. (2009). Robust and efficient surface reconstruction from range data. In: *Computer graphics forum*, 28(8):2275-2290. Oxford, UK: Blackwell Publishing Ltd.

Leberl, F. (2010). Time for neo-photogrammetry. *GIS Dev*, *14*(2):22-24.

Lee, J., Becker, T., Nagel, C., Kolbe, T. H., Sisi, Z. & Li, K. J. (2014). *OGC® IndoorGML*, Version 1.0.

Lee, B. M., Kim, T. J., Kwak, B. Y., Lee, Y. H. & Choi, J. (2015). Improvement of the Korean LADM country profile to build a 3D cadastre model. *Land Use Policy*, *49*, 660-667.

Lemmen, C. H. J. (2010). *The social tenure domain model: a pro-poor land tool*. FIG publication No 52.

Lemmen, C. & Van Oosterom, P. (2003). 3D Cadastres. *Computers, Environment and Urban Systems*, *27*(4):337-343.

Lemmen, C., Van Oosterom, P. & Bennett, R. (2015). The land administration domain model. *Land use policy*, *49*:535-545.

Li, L., Wu, J., Zhu, H., Duan, X. & Luo, F. (2016). 3D modeling of the ownership structure of condominium units. *Computers, environment and urban systems*, *59*:50-63.

Lorensen, W. E. & Cline, H. E. (1987). Marching cubes: A High Resolution 3D Surface Reconstruction Algorithm. *ACM Computer Graphics, 21* (4):163-169.

MagicPlan. (2022). *Sensopia MagicPlan*. http://www.sensopia.com/english/index.html (Accessed March 2022).

McLaren, R. (2011). *Crowdsourcing support of land administration: a new, collaborative partnership between citizens and land professionals*. Royal Institution of Chartered Surveyors (RICS) Report November, 32 p.

McLaren, R. (2012). Crowdsourcing Support for Land Administration – A Partnership Approach. In: *FIG Working Week 2012 - Knowing to manage the territory, protect the environment, evaluate the cultural heritage*. Rome, Italy, 6-10 May, 14 p.

Makantasis, K., Karantzalos, K., Doulamis, A. & Loupos, K. (2015). Deep learning-based man-made object detection from hyperspectral data. In: *International symposium on visual computing*, pp. 717-727. Springer, Cham.

Mayer, H. (1999). Automatic object extraction from aerial imagery—a survey focusing on buildings. *Computer vision and image understanding*, *74*(2):138-149.

Mayer, H. (2014). Efficient hierarchical triplet merging for camera pose estimation. In: *German Conference on Pattern Recognition*, pp. 399-409. Springer, Cham.

Mayer, H. (2015). From Orientation to functional Modeling for Terrestrial and UAV Images. In: *55th Photogrammetric Week*, Wichmann/VDE Verlag: Berlin/Offenbach, Germany, pp. 165-174.

McClune, A. P., Miller, P. E., Mills, J. P. & Holland, D. (2014). Automatic urban 3d building reconstruction from multi-ray photogrammetry. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XL-3, pp. 219–226. https://doi.org/10.5194/isprsarchives-XL-3-219-2014

McClune, A. P., Mills, J. P., Miller, P. E. & Holland, D. A. (2016). Automatic 3D building reconstruction from a dense image matching dataset. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B3, pp. 641–648. https://doi.org/10.5194/isprs-archives-XLI-B3-641-2016

McKay, A., Chase, S., Shea, K. & Chau, H. H. (2012). Spatial grammar implementation: From theory to useable software. *AI EDAM*, *26*(2):143-159.

Mena, J. B. (2003). State of the art on automatic road extraction for GIS update: a novel classification. *Pattern recognition letters*, *24*(16):3037-3058.

Milde, J. & Brenner, C. (2009). Graph-based modeling of building roofs. In: *AGILE Conference on GIScience*, Vol. 20, 5 p. https://www.ikg.uni-hannover.de/fileadmin/ikg/Forschung/publications/MildeBrenner_agile2009.pdf

Mnih, V. (2013). *Machine learning for aerial image labeling*. University of Toronto, Canada.

MOI. (2018). Moment of inertia and eccentricity based descriptors - Point Cloud Library (PCL). http://pointclouds.org/blog/hrcs/sushakov/index.php (Accessed April 2018).

Molendijk, M., Dukon, T.S., Lemmen, C., Morales, J., Endo, V., Rodriguez, S.R., Dueñas, J.F.G., Sanchez, I.E.M., Spijkers, P., Unger, E.M. & Horta, I.A.M. (201). Land and Peace in Colombia: FFP methodology for field data collection and data handling. In: *Proceedings of the World Bank Land and Poverty Conference*, Washington DC, USA.

Moons, T., Van Gool, L. & Vergauwen, M. (2010). 3D reconstruction from multiple images part 1: Principles. *Foundations and Trends® in Computer Graphics and Vision*, *4*(4):287-404.

Mourafetis, G., Apostolopoulos, K., Potsiou, C. & Ioannidis, C. (2015). Enhancing cadastral surveys by facilitating the participation of owners. *Survey review*, *47*(344):316-324.

Mourafetis, G. & Potsiou, C. (2020). IT services and crowdsourcing in support of the Hellenic Cadastre: advanced citizen participation and crowdsourcing in the official property registration process. *ISPRS International journal of geo-information*, *9*(4), 190.

Müller, P., Wonka, P., Haegler, S., Ulmer, A. & Van Gool, L. (2006). Procedural modeling of buildings. In: *ACM SIGGRAPH 2006 Papers*, pp. 614-623.

Myronenko, A. & Song, X. (2010). Point set registration: Coherent point drift. *IEEE transactions on pattern analysis and machine intelligence*, *32*(12):2262-2275.

Navratil, G. & Frank, A. U. (2013). VGI for land administration–a quality perspective. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XL-2/W1, p. 159-163.

Nguatem, W., Drauschke, M. & Mayer, H. (2016). Automatic Generation of Building Models with Levels of Detail 1-3. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B3, pp. 649–654. https://doi.org/10.5194/isprs-archives-XLI-B3-649-2016

Nielsen, J. (2012). Usability 101: Introduction to usability. https://www.nngroup.com/articles/usability-101-introduction-to-usability/ (Accessed September 2019).

Nister, D. (2004). Automatic passive recovery of 3D from images and video. In: *2nd International Symposium on 3D Data Processing, Visualization and Transmission, 2004 (3DPVT 2004)*, pp. 438-445. IEEE.

Noh, H., Hong, S. & Han, B. (2015). Learning deconvolution network for semantic segmentation. In: *IEEE International conference on computer vision*, pp. 1520-1528.

Nov, O. (2007). What motivates wikipedians? *Communications of the ACM*, *50*(11):60-64.

Oldfield, J., Van Oosterom, P., Beetz, J. & Krijnen, T. F. (2017). Working with open BIM standards to source legal spaces for a 3D cadastre. *ISPRS International Journal of Geo-Information*, *6*(11):351.

Oldfield, J., Van Oosterom, P., Quak, W., Van Der Veen, J. & Beetz, J. (2016, October). Can data from BIMs be used as input for a 3D Cadastre. In:*5th International FIG 3D Cadastre Workshop,* Athens, Greece, pp. 18-20.

Omidalizarandi, M. & Saadatseresht, M. (2013). Segmentation and classification of point clouds from dense aerial image matching. *The International Journal of Multimedia & Its Applications*, *5*(4), 33.

Oriol, X. & Teniente, E. (2014). Incremental Checking of OCL Constraints through SQL Queries. *OCL@ MoDELS*, *1285*, pp. 23-32.

OSM. (2022). Open Street Map https://www.openstreetmap.org (Accessed March 2022).

OSMstatistics. (2022). OSM statistics – taginfo https://taginfo.openstreetmap.org/keys/building#combinations (Accessed April 2022).

Over, M., Schilling, A., Neubauer, S. & Zipf, A. (2010). Generating web-based 3D City Models from OpenStreetMap: The current situation in Germany. *Computers, Environment and Urban Systems*, *34*(6):496-507.

Papaefthymiou, M., Labropoulos, T. & Zentelis, P. (2004). 3-D Cadastre in Greece–Legal, Physical and Practical Issues Application on Santorini Island. In: *FIG Working Week*, 16 p. https://www.fig.net/resources/proceedings/fig_proceedings/athens/papers/ts25/TS25_6_Labropoulos_et_al.pdf

PCL. (2018). Point Cloud Library (PCL). http://pointclouds.org/ (Accessed April 2018).

Peng, D., Zhang, Y. & Guan, H. (2019). End-to-end change detection for high resolution satellite images using improved UNet++. *Remote Sensing*, *11*(11), 1382.

Podolak, J. & Rusinkiewicz, S. (2005). Atomic Volumes for Mesh Completion. In: *Symposium on Geometry Processing*, pp. 33-41.

Pollefeys, M., Van Gool, L., Vergauwen, M., Verbiest, F., Cornelis, K., Tops, J. & Koch, R. (2004). Visual modeling with a hand-held camera. *International Journal of Computer Vision*, *59*(3):207-232.

Potsiou, C., Paunescu, C., Ioannidis, C., Apostolopoulos, K. & Nache, F. (2020). Reliable 2D crowdsourced cadastral surveys: case studies from Greece and Romania. *ISPRS International Journal of Geo-Information*, *9*(2), 89.

Pratt, W. (2001). *Digital Image Processing*. 3rd edition, John Wiley & Sons, New York. DOI:10.1002/0471221325.

QLD3D. (2022). Queensland Project: 3D indoor navigation and 3D augmented reality through the cadastral database, http://3dqld.org/ (Accessed April 2022).

Rajabifard, A., Agunbiade, M., Kalantari, M., Yip, K.M., Atazadeh, B., Badiee, B., Isa, D.M.N.B., Adimin, M.K.B., Chan, K.L., Aien, A., Olfat, H., Shojaei, D. & Anaraki, M.R. (2018). An LADM-based Approach for Developing and Implementing a National 3D Cadastre – A Case Study of Malaysia. In: *7th International FIG Workshop on the Land Administration Domain Model*, 11-13 April 2018, Zagreb, Croatia, pp. 47-66.

Remondino, F. & El-Hakim, S. (2006). Image-based 3D modelling: a review. *The photogrammetric record*, *21*(115):269-291.

Ronneberger, O., Fischer, P. & Brox, T. (2015, October). U-net: Convolutional networks for biomedical image segmentation. In: *International Conference on Medical image computing and computer-assisted intervention*, pp. 234-241. Springer, Cham.

Rönsdorff, C., Wilson, D. & Stoter, J. E. (2014). Integration of land administration domain model with CityGML for 3D Cadastre. In: *4th International Workshop on 3D Cadastres*, 9–11 November 2014, Dubai, United Arab Emirates, pp. 313–322.

Rottensteiner, F., Sohn, G., Gerke, M., Wegner, J. D., Breitkopf, U. & Jung, J. (2014). Results of the ISPRS benchmark on urban object detection and 3D building reconstruction. *ISPRS Journal of Photogrammetry and Remote Sensing*, *93*, pp. 256-271.

Rusu, R. B. (2010). Semantic 3D object maps for everyday manipulation in human living environments. *KI-Künstliche Intelligenz*, *24*(4):345-348.

Sahu, M. & Ohri, A. (2019). Vector map generation from aerial imagery using deep learning. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV-2/W5, pp. 157–162. https://doi.org/10.5194/isprs-annals-IV-2-W5-157-2019

Sarp, G., Erener, A., Duzgun, S. & Sahin, K. (2014). An approach for detection of buildings and changes in buildings using orthophotos and point clouds: A case study of Van Erriş earthquake. *European Journal of Remote Sensing*, *47*(1):627-642.

Scarponcini, P. (2016). *OGC® Land and Infrastructure Conceptual Model Standard (LandInfra)*, Version 1.0.

Scharstein, D. & Szeliski, R. (2002). A taxonomy and evaluation of dense two-frame stereo correspondence algorithms. *International journal of computer vision*, *47*(1):7-42.

Senaratne, H., Mobasheri, A., Ali, A. L., Capineri, C. & Haklay, M. (2017). A review of volunteered geographic information quality assessment methods. *International Journal of Geographical Information Science*, *31*(1):139-167.

Sequeira, V., Wolfart, E., Bovisio, E., Biotti, E. & Goncalves, J. G. (2000, December). Hybrid 3D reconstruction and image-based rendering techniques for reality modeling. In: *Videometrics and Optical Methods for 3D Shape Measurement*, 4309, pp. 126-136. International Society for Optics and Photonics.

Shin, J., Rajabifard, A., Kalantari, M. & Atazadeh, B. (2020). Applying BIM to support dispute avoidance in managing multi-owned buildings. *Journal of Computational Design and Engineering, 7*(6):788–802.

Shojaei, D., Olfat, H., Rajabifard, A., Darvill, A. & Briffa, M. (2016). Assessment of the Australian digital cadastre protocol (ePlan) in terms of supporting 3D building subdivisions. *Land use policy*, *56*, pp. 112-124.

Sîrbu, A., Becker, M., Caminiti, S., De Baets, B., Elen, B., Francis, L., Gravino, P., Hotho, A., Ingarra, S., Loreto, Molino, A., Mueller, J., Peters, J., Ricchiuti, F., Saracino, F., Servedio, V. D. P., Stumme, G., Theunis, J., Tria, F. & Van den Bossche, J. (2015). Participatory patterns in an international air quality monitoring initiative. *PLOS one*, *10*(8): e0136763. https://doi.org/10.1371/journal.pone.0136763

Snavely, N., Seitz, S. M. & Szeliski, R. (2008). Modeling the world from internet photo collections. *International journal of computer vision*, *80*(2):189-210.

Sohn, G. & Dowman, I. (2007). Data fusion of high-resolution satellite imagery and LiDAR data for automatic building extraction. *ISPRS Journal of Photogrammetry and Remote Sensing*, *62*(1):43-63.

Somogyi, A., Barsi, A., Molnar, B. & Lovas, T. (2016). Crowd sourcing based 3d modeling. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XLI-B5, pp. 587-590.

Soon, K.H., Thompson, R. & Khoo, V. (2014). Semantics-based Fusion for CityGML and 3D LandXML. In: *4th International Workshop on 3D Cadastres*, pp. 323–338. Dubai, United Arab Emirates.

Shorten, C. & Khoshgoftaar, T. M. (2019). A survey on image data augmentation for deep learning. *Journal of big data*, *6*(1):1-48.

Shum, H. & Kang, S. B. (2000, May). Review of image-based rendering techniques. In *Visual Communications and Image Processing 2000*, 4067, pp. 2-13. SPIE.

Stoter, J., Ploeger, H., Roes, R., van der Riet, E., Biljecki, F. & Ledoux, H. (2016). First 3D cadastral registration of multi-level ownerships rights in the Netherlands. In: *5th International FIG 3D Cadastre Workshop,* Athens, Greece, pp. 18-20.

Stoter, J., Ho, S. & Biljecki, F. (2019). Considerations for a contemporary 3D cadastre for our times. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-4/W15, pp. 81–88, https://doi.org/10.5194/isprs-archives-XLII-4-W15-81-2019

Stoter, J. E. & van Oosterom, P. (2005). Technological aspects of a full 3D cadastral registration. *International Journal of Geographical Information Science*, *19*(6):669-696.

Stoter, J. E., van Oosterom, P. & Ploeger, H. D. (2012). The phased 3D cadastre implementation in the Netherlands. In: *3rd International FIG Workshop on 3D Cadastres: Developments and practices*, Shenzhen, China, 25-26 October, pp. 203-218. https://www.fig.net/resources/proceedings/2012/2012_3d_workshop/ss4_STOTER.pdf

Stubkjær, E., Paasch, J. M., Cagdas, V., van Oosterom, P., Simmons, S., Paulsson, J. & Lemmen, C. (2018). International code list management–the case of land administration. In: *7th International FIG Workshop on the Land Administration Domain Model*, pp. 11-13.

Taillandier, F. (2005). Automatic building reconstruction from cadastral maps and aerial images. *International Archives of Photogrammetry and Remote Sensing*, XXXVI(Part 3)/W24.

Tekavec, J. & Lisec, A. (2020). Cadastral data as a source for 3D indoor modelling. *Land use policy*, *98*, 104322.

Thompson, R., van Oosterom, P., Soon, K. H. & Priebbenow, R. (2016). A Conceptual Model supporting a range of 3D parcel representations through all stages: Data Capture, Transfer and Storage. In: *FIG Working Week 2016 "Recovery from disaster"*, Christchurch, New Zealand, May 2-6, 23 p.

Tuia, D. & Camps-Valls, G. (2010). Urban image classification with semisupervised multiscale cluster kernels. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *4*(1):65-74.

Tulloch, D. L. (2008). Is VGI participation? From vernal pools to video games. *GeoJournal*, *72*(3):161-171.

Uden, M. & Zipf, A. (2013). Open building models: Towards a platform for crowdsourcing virtual 3D cities. In: *Progress and new trends in 3D geoinformation sciences*, pp. 299-314. Springer, Berlin, Heidelberg.

Vakalopoulou, M., Karantzalos, K., Komodakis, N. & Paragios, N. (2015). Building detection in very high resolution multispectral data with deep learning features. In: *2015 IEEE international geoscience and remote sensing symposium (IGARSS)*, pp. 1873-1876.

Vallet, B., Pierrot-Deseilligny, M. & Boldo, D. (2009). Building footprint database improvement for 3D reconstruction: a direction aware split and merge approach. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVIII, Part 3/W4, pp. 139-144. https://www.isprs.org/proceedings/xxxviii/3-w4/pub/CMRT09_139.pdf

van Oosterom, P. (2013). Research and development in 3D cadastres. *Computers, Environment and Urban Systems, 40*:1-6.

van Oosterom, P., Erba, D. A., Aien, A., Grant, D., Kalantari, M., Karki, S., Shojaei, D., Thompson, R., Muggenhuber, G., Navratil, G., Dixit, N., Kashram, A.R., Flávia A., Carneiro, T., Brochu, F., Desbiens, L.A, Egesborg, P., Gervais, M., Pouliot, J., Roy, F., Guo, R., Ning, Z., Ying, S., Bolaños, A.H, Roic, M., Elia, E., Janecka, K., Bodum, L., Sørensen, E.M., Thellufsen, C., Hokkanen, J., Kokkonen, A., Myllymäki, T., Galpin, C., Halbout, H., Seifert, M., Dimopoulou, E., Iván, G., Osskó, A., Ghawana, T., Khandelwal, P., Aditya, T., Subaryono, S., Doytsher, Y., Forrai, J., Kirschner, G., Tal, Y., Navarra, D., Razza, B., Rispoli, E., Savoldi, F., Khairudinova, N., Siriba, D., Gjorgjiev, G., Gjorgjiev, V., Hua, T.C., Rahman, A.A., Acharya, B.R., van Dam, B., Lemmen, C., Ploeger, H., Rijsdijk, M., Stoter, J., Dabiri, T., Elsrud, L., Jenssen, O., Lobben, L., Valstad, T., Bydlosz, J., Karabin, M., de Almeida, J.P.E.D., de Oliveira, J.P.F.H., Magarotto, M., Sapelnikov, S., Vandysheva, N., Mihajlovic, R., Visnjevac, N., Khoo, V., Soon, K.H., Lee, Y., Velasco, A., Ekbäck, P., Paasch, J., Paulsson, J., Boss, H.A., Balanche, R., Niggeler, L., Griffith-Charles, C., Biyik, C., Demir, O., Döner, F., Robson, G., Rönsdorf, C., Ader, B., Cowen, D., Reed, C. & Smith, A. (2018). *Best Practices 3D Cadastres: Extended Version*. FIG Publication. https://www.fig.net/resources/publications/figpub/FIG_3DCad/FIG_3DCad-final.pdf

Vandysheva, N., Tikhonov, V., Van Oosterom, P. J. M., Stoter, J. E., Ploeger, H. D., Wouters, R. & Penkov, V. (2011). 3D Cadastre modelling in Russia. In: *FIG Working Week 2011 "Bridging the Gap between Cultures" & 6th National Congress of ONIGT*, Marrakech, Morocco, 18-22 May. International Federation of Surveyors (FIG); Ordre National des Ingénieurs Géomètres Topographes (ONIGT).

Vapnik, V. (1999). *The nature of statistical learning theory*. Springer Science & Business Media.

Verykokou, S. & Ioannidis, C. (2016). Exterior orientation estimation of oblique aerial imagery using vanishing points. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.,* XLI-B3, pp. 123–130. https://doi.org/10.5194/isprs-archives-XLI-B3-123-2016

Vincent, L. & Soille, P. (1991). Watersheds in digital spaces: an efficient algorithm based on immersion simulations. *IEEE Transactions on Pattern Analysis & Machine Intelligence, 13*(06): 583-598.

VTK. (2018). The Visualization Toolkit (VTK) https://www.vtk.org/ (Accessed April 2018).

Vučić, N., Cetl, V. & Roić, M. (2015). How to Utilize the Citizens to Gather VGI as a Support for 3D Cadastre Transition. In*: FIG Workshop 2015 "Crowdsourcing of Land Information"*. bib.irb.hr/datoteka/862026.Malta_v_2.0_web.pdf.

Wang, Y. (2012). Automatic extraction of building roofs from pictometry's orthogonal and oblique images. *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, 39:361-365. DOI:10.5194/isprsarchives-XXXIX-B3-361-2012

Wang, Y. (2016). Automatic extraction of building outline from high resolution aerial imagery. *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, XLI-B3, pp. 419-423. DOI:10.5194/isprs-archives-XLI-B3-419-2016

Wang, K., Fan, X. & Wang, Q. (2022). FPB-UNet++: Semantic Segmentation for Remote Sensing Images of reservoir area via Improved UNet++ with FPN. In: *6th International Conference on Innovation in Artificial Intelligence (ICIAI)*, pp. 100-104.

Weng, J., Huang, T. S. & Ahuja, N. (2013). Motion and structure from image sequences, *Springer Series in Information Sciences*, vol. 29.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. & Reynolds, J. M. (2012). 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, *179*:300-314.

Wichmann, A., Jung, J., Sohn, G., Kada, M. & Ehlers, M. (2015). Integration of building knowledge into binary space partitioning for the reconstruction of regularized building models. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, II-3/W5, pp. 541–548, https://doi.org/10.5194/isprsannals-II-3-W5-541-2015

Williamson, I., Rajabifard, A., Kalantari, M. & Wallace, J. (2012). AAA Land Information: Accurate, Assured and Authoritative. *In: 8th FIG Regional Conference 2012 Surveying towards Sustainable Development.* Montevideo, Uruguay, pp. 26–29.

Wonka, P., Wimmer, M., Sillion, F. & Ribarsky, W. (2003). Instant architecture. *ACM Transactions on Graphics (TOG)*, *22*(3):669-677.

Wu, G., Shao, X., Guo, Z., Chen, Q., Yuan, W., Shi, X., Xu, Y. & Shibasaki, R. (2018). Automatic building segmentation of aerial imagery using multi-constraint fully convolutional networks. *Remote Sensing*, *10*(3), 407.

Wu, G., Guo, Z., Shi, X., Chen, Q., Xu, Y., Shibasaki, R. & Shao, X. (2018). A boundary regulated network for accurate roof segmentation and outline extraction. *Remote Sensing*, *10*(8), 1195.

Xu, Z., Wu, T. H., Shen, Y. & Wu, L. (2016). Three dimentional reconstruction of large cultural heritage objects based on uav video and tls data. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B5, pp. 985–988. https://doi.org/10.5194/isprs-archives-XLI-B5-985-2016

Xu, J., Zhao, L., Zhang, S., Gong, C. & Yang, J. (2020). Multi-task learning for object keypoints detection and classification. *Pattern Recognition Letters*, *130*:182-188.

Ying, S., Guo, R., Li, L., Van Oosterom, P. & Stoter, J. (2015). Construction of 3D volumetric objects for a 3D cadastral system. *Transactions in GIS*, *19*(5):758-779.

Yu, Q., Helmholz, P. & Belton, D. (2016). Evaluation of model recognition for Grammar-based automatic 3d building model reconstruction. *The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences*, XLI-B4, pp. 63-69. DOI:10.5194/isprs-archives-XLI-B4-63-2016

Yu, Q., Helmholz, P., Belton, D. & West, G. (2014). Grammar-based automatic 3D model reconstruction from terrestrial laser scanning data. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XL-4, pp. 335–340. https://doi.org/10.5194/isprsarchives-XL-4-335-2014

Zhang, Z., Huang, S. & Duan, Y. (2016). Dense image matching with two steps of expansion. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLI-B3, pp. 143–149. https://doi.org/10.5194/isprs-archives-XLI-B3-143-2016

Zhang, Y., Sohn, K., Villegas, R., Pan, G. & Lee, H. (2015). Improving object detection with deep convolutional networks via bayesian optimization and structured prediction. In: *IEEE Conference on Computer Vision and Pattern Recognition*, pp. 249-258.

Zhao, Y., Zhou, X., Li, G. & Xing, H. (2016). A spatio-temporal VGI model considering trust-related information. *ISPRS International Journal of Geo-Information*, *5*(2):10.

Zhao, H., Zhang, H. & Zheng, X. (2022). A multiscale attention-guided UNet++ with edge constraint for building extraction from high spatial resolution imagery. *Applied Sciences*, *12*(12), 5960.

Zhou, Z., Rahman Siddiquee, M. M., Tajbakhsh, N. & Liang, J. (2018). Unet++: A nested u-net architecture for medical image segmentation. In: *Deep learning in medical image analysis and multimodal learning for clinical decision support*, pp. 3-11. Springer, Cham.

Zhu, J. & Wu, P. (2021). A common approach to geo-referencing building models in industry foundation classes for BIM/GIS integration. *ISPRS International Journal of Geo-Information*, *10*(6):362.

Zlatanova, S., van Oosterom, P., Lee, J., Li, K. J. & Lemmen, C. H. J. (2016). LADM and IndoorGML for support of indoor space identification. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, IV-2/W1, pp. 257–263. https://doi.org/10.5194/isprs-annals-IV-2-W1-257-2016

Zlatanova, S., Li, K. J., Lemmen, C. & van Oosterom, P. (2016). Indoor abstract spaces: linking IndoorGML and LADM. In: *5th International FIG 3D Cadastre Workshop*, pp. 317-328.

Zulkifli, N. A., Abdul Rahman, A. & van Oosterom, P. (2014). 3D Strata Objects Registration for Malaysia within the LADM Framework. In: *4th International FIG 3D Cadastre Workshop*, 9-11 November 2014, Dubai, United Arab Emirates, pp. 379-390.

Zulkifli, N. A., Rahman, A. & van Oosterom, P. (2015). An overview of 3D topology for LADM-based objects. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XL-2/W4, pp. 71–73. https://doi.org/10.5194/isprsarchives-XL-2-W4-71-2015