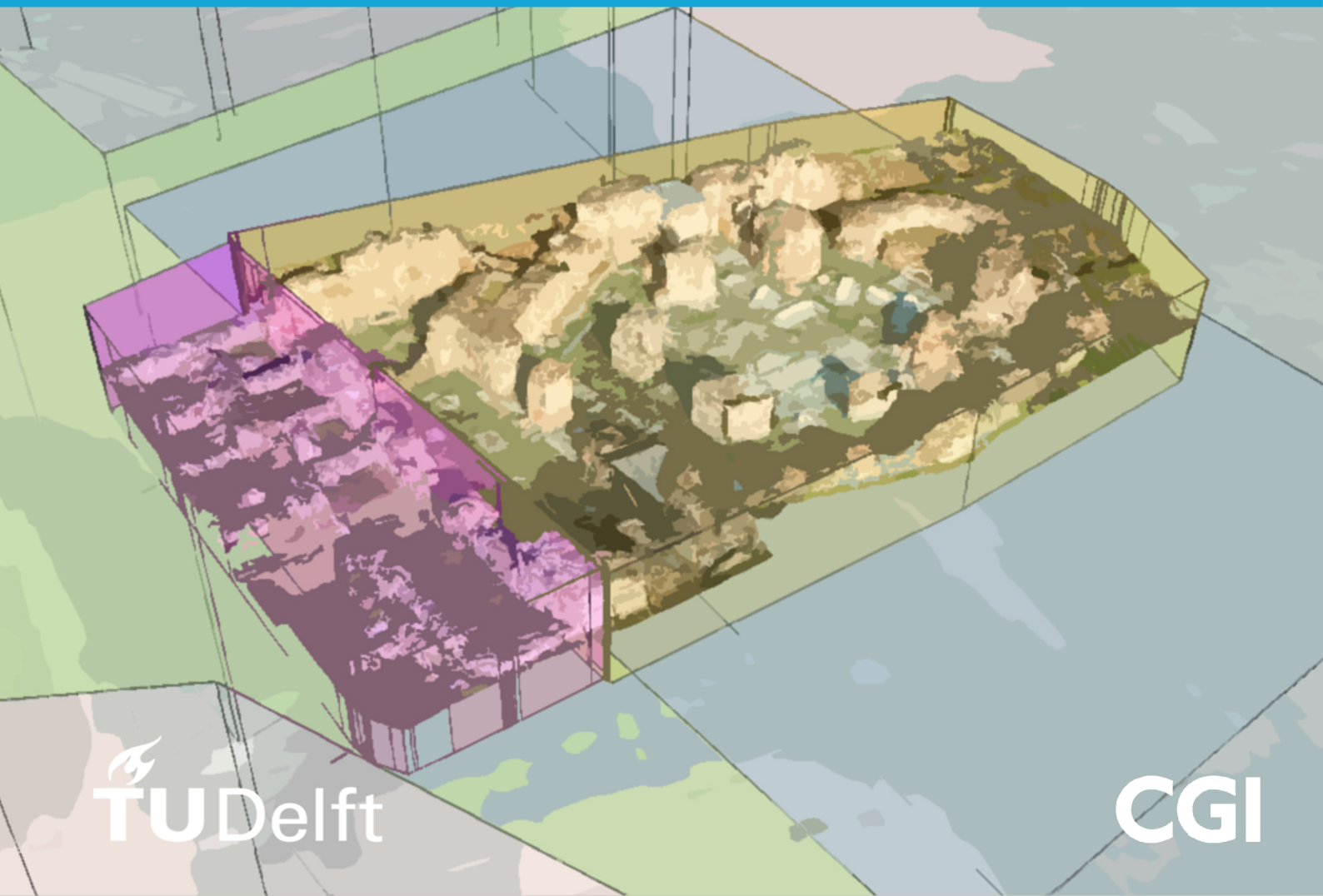
MSc thesis in Geomatics

LADM-based 3D system for Archaeological Site Information Registration

Dimitrios Mouzakidis
2025



TU Delft

CGI

MSc thesis in Geomatics

LADM-based 3D system for Archaeological Site Information Registration

Dimitrios Mouzakidis

October 2025

A report submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of Master of Science in Geomatics

Dimitrios Mouzakidis: *LADM-based 3D system for Archaeological Site Information Registration* (2025)

The work in this thesis is carried out in the:

Geo-Database Management Center
Delft University of Technology

and the:

CGI NEDERLAND B.V

Supervisors:	Prof. Dr. Ir. Peter van Oosterom
	Dr. Eftychia Kalogianni
Company Supervisor:	Ir. Robert Voûte
Co-reader:	Prof. Mila Koeva

Abstract

This thesis develops an LADM-based (ISO 19152-2) profile for the legal registration and management of archaeological heritage in three dimensions. The research addresses the need to represent rights, restrictions, and responsibilities of protected sites while capturing their full vertical extent and linking them to cadastral information. A structured Design Science Research methodology guided the work from problem definition to model design. The resulting archaeological profile extends the core LADM packages, namely Party, Administrative, Spatial Unit, and Surveying and Representation, to meet archaeological requirements. Point clouds are integrated into the model to represent archaeological spatial units in 3D, ensuring that the geometry of protected areas can be recorded and maintained with high precision. The archaeological profile demonstrates that the LADM standard can accommodate archaeological contexts by unifying legal, spatial, and survey information in a single framework. This work provides a comprehensive, conceptual,and database-ready model that enables accurate 3D registration, querying, and visualization of archaeological sites and offers a solid foundation for future cross-jurisdictional and international applications.

Acknowledgements

In this section, I would like to take the opportunity to thank a few people who had an impact on the completion of this research.

First, I would like to sincerely thank my academic supervisors at TU Delft, Prof. Peter van Oosterom and Dr. Eftychia Kalogianni, for their valuable guidance, constructive feedback, and continuous support throughout this project. Their insights helped me navigate both the conceptual and technical aspects of my research with greater clarity and confidence.

A special thanks goes to my company supervisor at CGI, Robert Voûte. His guidance went far beyond technical supervision, he was a mentor and a source of constant encouragement throughout this journey. His openness, patience, and genuine care often reminded me of home and helped me stay positive when things became overwhelming. I am deeply grateful for his support, both professionally and personally.

I would also like to thank the Ephorate of Antiquities of the Region of Rhodope in north-eastern Greece and the Municipality of Riemst in Belgium, and specifically Mike Lahaye, for kindly providing archaeological data used in this research. Their collaboration and willingness to share information from their sites made it possible to develop and validate this work.

I owe my deepest thanks to my family, my parents and my sister, for their endless love and belief in me. Their support, patience, and encouragement have been my foundation throughout my studies. No matter the distance, their words always reached me at the right time.

Lastly, to my friends and classmates, thank you for being there through all the ups and downs, for the study sessions, the laughs, and the moments of distraction that helped me keep my balance. You made this journey so much more memorable, and I am grateful to have shared it with you.

Contents

1. Introduction **1**
- 1.1. General Overview . . . 1
- 1.2. Research Objectives . . . 2
- 1.3. Thesis outline . . . 2

2. Literature Review **3**
- 2.1. Land Administration & Standardization . . . 3
- 2.2. Land Administration Domain Model . . . 3
- 2.3. 3D LADM related work . . . 5
- 2.4. Archaeological Data Infrastructures . . . 6
  - 2.4.1. The Netherlands . . . 6
  - 2.4.2. Belgium . . . 7
  - 2.4.3. Greece . . . 7
- 2.5. Requirements Identification . . . 8

3. Methodology **10**
- 3.1. Research Methodology . . . 10
- 3.2. Design Decisions . . . 11
  - 3.2.1. Scope . . . 11
  - 3.2.2. Legal Framework & RRRs . . . 12
  - 3.2.3. Archaeological Unit Definition . . . 13
  - 3.2.4. Temporal Management and Versioning . . . 14

4. Profile Development **15**
- 4.1. Core Classes . . . 15
- 4.2. Additional Classes . . . 16
- 4.3. Relationships & Multiplicities . . . 17

5. Evaluation of the proposed model **21**
- 5.1. Case studies . . . 21
- 5.2. Pre-processing . . . 22
- 5.3. Instance Level Diagrams . . . 23
- 5.4. Database Implementation . . . 24
  - 5.4.1. Party package . . . 25
  - 5.4.2. Administrative package . . . 25
  - 5.4.3. Spatial Unit package . . . 26
  - 5.4.4. Surveying & Representation Package . . . 27
  - 5.4.5. Database Population . . . 28
- 5.5. Queries . . . 31
- 5.6. Visualizations . . . 34

6. Conclusions and Discussion **37**
6.1. Concluding Remarks 37
6.2. Discussion 38
6.3. Limitations and Future Work 39

A. Reproducibility self-assessment **40**
A.1. Marks for each of the criteria 40
A.2. Self-reflection 41

List of Figures

2.1. LADM Edition II Parts 1, 2 4

3.1. Design Science Research Cycles (Hevner & Chatterjee, 2010) 10
3.2. Research Methodology 11

4.1. Classes of the proposed model 15
4.2. Additional Classes of the proposed model 17
4.3. Classes and Relationships of the proposed model 19

5.1. Byzantine Wall (Urban case) 21
5.2. Mosynopolis (Rural case) 22
5.3. Point cloud of Quarry Grote Berg 22
5.4. Basic Administrative Unit with two and with one spatial components 24
5.5. Basic Administrative Units in two different countries 24
5.6. Arch3d_party table included the party role description 30
5.7. Arch3d_baunit table 30
5.8. Arch3d_right table 30
5.9. Arch3d_right table 30
5.10. Arch3d_pointcloudobservation table 31
5.11. Land Administration Domain Model (LADM) Database Structure 31
5.12. Query 1 33
5.13. Query 2 34
5.14. Visualization of the rural Greek case study showing cadastral parcels (blue and green) and corresponding 3D archaeological volumes (yellow and pink). . 34
5.15. Parcel-based classification for 3D Archaeological Spatial Units Identification . 35
5.16. 3D visualization of the cross-border case study 36

A.1. Reproducibility criteria to be assessed. 40

Acronyms

LAS Land Administration System 1
LA Land Administration 3
LADM Land Administration Domain Model ix
ISO International Standards 1
SDI Spatial Data Infrastructures 4
RRR Rights, Restrictions amd Responsibilities 1

1. Introduction

This chapter introduces the thesis topic and establishes the foundation for the research by presenting the overall context, the main objectives, and the guiding research questions. It also clarifies the scope of the study and concludes with an outline of the thesis structure.

1.1. General Overview

Recent advances in geospatial technologies and 3D data acquisition have reshaped how land and cultural heritage are documented, analyzed, and managed. Within this evolving context, cadastral and Land Administration System (LAS) are increasingly expected to represent not only surface parcels but also complex underground and above-ground spaces. The lifecycle of a 3D object in the built environment encompasses planning, design, construction, registration, and operation, with information flowing across these phases [Kalogianni et al., 2020]. Heritage sites, as unique land components, are such 3D objects that demand particular attention within modern cadastral and LASs. However, despite advances in handling complex 3D environments and layered property rights, cadastral systems often overlook the detailed registration of areas with cultural and archaeological significance. In addition, the volume and granularity of geospatial data collected for heritage documentation continue to grow, offering new opportunities but also raising new challenges for capturing legal and spatial realities more accurately.

Among these data, point clouds have emerged as a particularly valuable resource due to their ability to represent physical structures in high-resolution 3D. Their widespread use in heritage documentation raises a critical question; can point clouds also serve as a valid form of boundary representation of the legal spaces within land administration systems? This issue is especially relevant in contexts where Rights, Restrictions amd Responsibilities (RRR) are either unregistered or require refinement to reflect the true extent and nature of protected archaeological spatial units.

At the same time, International Standards (ISO) have gained importance in recent years by providing a shared vocabulary for the scientific documentation of Cultural Heritage (CH) [Psomadaki et al., 2016]. The utilization of these standards leads specialists such as archaeologists, maintainers, ICT experts, and engineers to the utilization of conformed methods for the successful recordation of the CH. In this sense, a standard in CH modeling can be understood as a set of regulations ensuring the correct development and protection of digital data produced through heritage documentation.

In this context, and based on the LADM, this research develops an LADM-based archaeological profile that employs point clouds to represent spatial unit boundaries, with requirements identified through case studies.

1.2. Research Objectives

Building on the challenges and opportunities outlined above, this section introduces the research questions and the scope that guide the thesis. The main research question as well as the sub-questions are listed below:

How can point cloud data be processed so that they can serve as boundary representations within LADM-based applications for archaeological purposes?

- What is the LADM archaeological profile that should be developed?
- How can boundary patches be selected from point cloud data for use in archaeological applications?
- How to link legal and semantic information with point clouds for archaeological purposes in the context of LADM?
- How can point cloud–based boundary representations be structured to enable effective querying, visualization, and validation within LADM-based archaeological applications?

The scope of this thesis is to integrate point clouds into LADM by developing an archaeological profile tailored to heritage documentation. The profile is evaluated and validated through its mapping into an LADM-compliant database, demonstrating how point cloud–based spatial unit boundaries can be linked with legal and semantic information. In this way, the research contributes a structured solution that supports both the preservation of legal property rights and the in-depth study of CH.

1.3. Thesis outline

The remainder of this thesis is structured as follows. Chapter 2 presents the literature review, discussing archaeological data infrastructures, land administration and standardization efforts, the Land Administration Domain Model (LADM), and the role of point clouds, and concludes with a gap analysis that motivates the proposed profile. Chapter 3 describes the research design, which follows the Design Science Research (DSR) paradigm, and explains how the research questions are addressed through iterative cycles. Chapter 4 outlines the requirements, design, and structure of the proposed LADM-based archaeological profile, including the definition of classes, relationships, and attributes. Chapter 5 demonstrates the application of the developed profile by presenting instance-level diagrams, database implementation, queries, and the case studies used to validate the approach. Finally, Chapter 6 summarizes the findings, answers the research questions, and reflects on limitations, contributions, and directions for future research.

2. Literature Review

This chapter establishes the foundation of the research by reviewing existing literature and identifying the key concepts, standards, and approaches relevant to the study.

2.1. Land Administration & Standardization

Land Administration (LA) encompasses the processes of recording and disseminating information about the ownership, value, and use of land and its associated resources, integrating land registry, cadastre, valuation, and land-use planning functions [Van Oosterom et al., 2020]. Within this system, the cadastre provides the authoritative spatial framework. A parcel-based, up-to-date record of land ownership rights that supports secure property transactions, taxation, and spatial planning [Van Oosterom, 2018].

Traditionally, cadastral systems have relied on 2D representations. However, increasing urban density, high-rise development, and the expansion of subsurface infrastructure have revealed the limits of purely 2D models. Overlapping rights such as stacked apartments, underground tunnels, and utilities cannot be unambiguously recorded on a flat map. As Van Oosterom et al. [2020] emphasize, "the increasing complexity of densely built-up areas and infrastructures requires proper registration of the legal status of the built environment which only can be provided to a limited extent by existing 2D representations". Accurate 3D LA is therefore critical to manage vertical property rights, enable sustainable development, and support modern urban planning.

Meeting these demands requires standardization. A common conceptual framework that ensures interoperability between agencies and countries, allows efficient data sharing, and supports integration with related domains. Without shared standards, cadastral data remain fragmented, making it difficult to manage rights, restrictions, and responsibilities consistently across jurisdictions and technologies. To address these challenges, the international community has developed the LADM, a formal, extensible standard that provides a unified vocabulary and data model for both the legal and spatial aspects of land administration, including 3D representations. The next section explores the LADM in detail and highlights best practices and applications relevant to this research.

2.2. Land Administration Domain Model

LADM, officially recognized as ISO 19152, is a globally acknowledged ISO standard. It is a standardized framework designed to support the efficient and interoperable management of land administration systems. To put it simple, people, organizations, states (party) create among themselves sets of obligations (RRR) with the specificity of having a geographical

component (spatial unit). It aims to establish a shared ontology for improved communication across organizations and countries, facilitate the development of adaptable application software, and enable seamless cadastral data exchange within Spatial Data Infrastructures (SDI) [Lemmen et al., 2015]. The three main packages of LADM Edition I are Party, Administrative, and Spatial Unit, all of which were contained under a single standard (ISO 19152:2012). This meant that a single, comprehensive document contained all of the model's features and components. Nevertheless, a multi-part structure is introduced by LADM Edition II [Lemmen et al., 2021], where the standard is split into distinct standards, each of which addresses particular issues of land management in greater depth. Thus, five standalone standards (Parts) have been produced as a multi-part structure that is backward compatible with Edition I [Kara et al., 2024], with the latest edition being ISO 19152-1:2024. These are the following:

- **Part 1** - Fundamentals
- **Part 2** - Land Registration
- **Part 3** - Marine Space Georegulation
- **Part 4** - Valuation Information
- **Part 5** - Spatial Plan Information
- **Part 6** - Implementation Aspects

According to ISO, Part 2 of the standard provides an abstract, conceptual model with three packages related to parties (people and organizations), basic administrative units, RRR, and spatial units (parcels, and the legal space of buildings and utility networks and other geometry), and one sub-package related to surveying and spatial representation (geometry and topology). The sub-package provides the methodologies and standards necessary for capturing, managing, and representing survey-related information in land administration systems. The refined survey model introduced by Kalogianni et al. [2024], plays a key role in improving interoperability with other standards and accommodating a variety of data acquisition techniques, including the integration of point cloud data, which is a core aspect of this research. Figure 2.1 presents the conceptual class diagram of LADM Edition II, Parts 1 and 2, which serves as the foundation for the research conducted in this study.

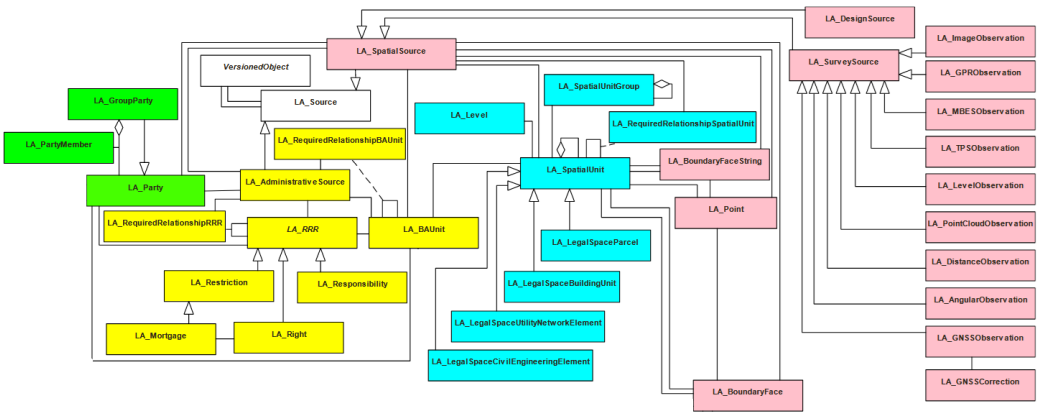


Figure 2.1.: LADM Edition II Parts 1, 2

2.3. 3D LADM related work

Recently, significant progress has been made in the conceptualization and implementation of 3D LASs for various types of 3D objects that require such management. An example is Ramlakhan et al. [2023] who presented a workflow to model RRR of 3D underground objects stored in an IFC (International Foundation Class) format highlighting the mapping of LADM classes to IFC entities. Approximately 44 datasets, mainly from the Netherlands, were collected for this research. However, only 9 of them are in IFC format, while the rest are in various other formats. Moreover, an LADM-based 3D underground utility data model for Singapore was created by Yan et al. [2019] along with a consolidated database in ArcGIS where for each land parcel the corresponding underground utilities can be displayed. Although various data collection techniques such as laser scanning, photogrammetry, and Ground Penetrating Radar (GPR) were used in this research, generating a variety of data formats for potential integration into the proposed data model, only data in dwg format was ultimately used after the primary data was post-processed. Moving above the ground, Van Oosterom et al. [2021] builds a 3D LAS prototype based on LADM using complex building structures stored in IFC format highlighting the importance of the as-designed and as-built nature of the models in a 3D LAS.

While much emphasis is placed on relatively modern 3D objects such as underground networks, utility networks, and complex buildings, historically significant objects, such as archaeological sites, also require similar attention. Bieda et al. [2020] researches the integration of historical underground structures into 3D cadastral systems, using a case study in Poland. The study highlights that many historical underground objects, built centuries ago, were not included in modern cadastral systems, leading to discrepancies in parcel boundaries. The authors proposed a new LADM-based data model to incorporate such structures into cadastral databases, ensuring accurate representation and legal clarity for 3D cadastral models.

Koeva et al. [2019] extend this perspective by demonstrating how multi-epoch point cloud data can support the detection of indoor spatial changes and their integration into a 3D cadastre. Their method automatically distinguishes permanent structural modifications (e.g., walls, rooms) from temporary changes (e.g., furniture) and links these to LADM classes such as LA_SpatialUnit and LA_RRR, thereby enabling updates to a 3D indoor cadastre. By leveraging point clouds to capture and compare building states at different times, the study illustrates how point cloud–derived volumetric boundaries can provide precise, up-to-date inputs for cadastral databases.

Psomadaki et al. [2016] proposes a 3D Hellenic Archaeological Cadastre based on LADM, providing a framework to register and manage archaeological sites' spatial and legal characteristics. Although a fully implemented 3D LAS is not described, the conceptualization and development of a LADM-based model and its integration into the existing cadastral framework in Greece are reported. Kalogianni et al. [2017] builds on this model and takes a step further by implementing a technical prototype using INTERLIS, expanding on the conceptual model by addressing technical implementation challenges. Although real data were gathered and a technical model was created, the visualization aspect remained undeveloped, with the discussion pointing to potential solutions such as CityGML and IFC formats due to their semantic capabilities.

To enable the diverse 3D LADM applications described above, a structured methodology for profile development is essential. Kalogianni et al. [2021] emphasize that experience from numerous national implementations demonstrates the need for a clear, repeatable process to

ensure legal, institutional, and technical consistency. They propose a three-phase framework that captures best practices. Such a methodology provides the foundation for translating national requirements into a ISO 19152-compliant profile.

2.4. Archaeological Data Infrastructures

This section reviews the archaeological data infrastructures of the Netherlands, Greece, and Belgium. These countries are examined because they serve as case studies for the validation of the proposed model later in this thesis.

2.4.1. The Netherlands

Archaeological information in the Netherlands is mainly managed by National Agency for Cultural Heritage (RCE) which falls under the Ministry of Education, Culture and Science. RCE operates the archaeological information system (Archaeological Information System (Archis)) which is a reference system for registering and consulting data on archaeological research, finds, traces, structures, complexes, and archaeological national monuments, from prehistoric to modern times in the Netherlands [Theunissen, 2024]. In addition to Archis, the RCE also manages the Monument Register (Monumentenregister), which is the official legal register of protected monuments, including archaeological monuments. The Heritage Act [Netherlands, 2016] is a Dutch law that brought together and modernized the main Dutch laws on cultural heritage, including the former Law on Monuments [Netherlands, 1988]. Once designated under the Heritage Act, a site or a monument is entered into the Monument Register. RCE has also developed Archaeological Monuments Map (AMK) which was also derived from Archis data combined with expert assessmnets, and it's a thematic product where sites are categorized into "very high", "high", or "archaeological value". After the Heritage Act, management of archaeological values became decentralized (municipalities, provinces), so AMK was frozen as a static dataset. Archis and the Monument Register continue to be living systems for recording archaeological data.

Moreover, the relationship between monument registration and legal protection has been discussed extensively in the literature. As Stoter [2004] describes, the Law on Monuments protects not only buildings or parts of buildings of monumental value, but also subsurface layers of archaeological significance. Under this law, restrictions may be imposed on monument owners, for example prohibiting the rebuilding of certain parts of a house. In the cadastral registration these restrictions are recorded at the parcel level using the code MW (or MWD when only part of the parcel is affected), while the precise geometry of the monument or archaeological site is not maintained. This practice often results in an entire parcel being characterized with a restriction even though, in reality, only the façade or part of a building is designated as a monument. Stoter [2004] further notes, the cadastral registration could be significantly improved by incorporating 2D or even 3D spatial descriptions of monuments and underground spaces, which would allow a more accurate registration of the protected parts of a parcel. This need is reinforced by European directives that require planners of new projects to consider archaeological remains in the subsurface, and by the fact that monument owners may receive state funding for conservation. More recent work by Buiza and Hekman [2022] partially confirms this vision, describing collaboration between the Dutch Cadastre (Kadaster) and the RCE to include archaeological restrictions in

the Public Law Restrictions (PLR) datasets. As a result, restrictions under the Heritage Act can now be directly linked to the cadastral parcels to which they apply, facilitating better decision making.

2.4.2. Belgium

Belgium is a federal state composed of three regions, Flanders, Wallonia, and the Brussels Capital Region each with its own legislative powers over immovable cultural heritage, including archaeological sites and monuments. This means that heritage management and archaeological data infrastructure are regionally governed. For example, in Flanders, heritage matters are regulated under the Immovable Heritage Decree which combines earlier laws related to immovable heritage existed [Vlaanderen, 2013]. Capacity for archaeological work, including approvals, inventories, standards, and archiving is assigned to the Flanders Heritage Agency [FHA, 2011].

The Flanders Heritage Agency provides public access to all official immovable heritage designations in a structured way. Data are grouped under four top-level designation types, protected heritage, established heritage, UNESCO world heritage, and areas not related to archaeology.

For archaeological and monuments data specifically, users can explore the protected heritage branch. Within this branch, the "protected archaeological site" category contains officially designated archaeological zones, while the "protected monument" and "protected townscape or village view" categories cover listed buildings and ensembles of monuments.

Unlike the Netherlands where PLR are directly integrated with the national cadastre, Flanders does not maintain a single PLR-style register. According to the Immovable Heritage Decree each designation explicitly reference the relevant cadastral parcels and include a plan of their boundaries. The federal cadastral database remains separate, but the Flanders Heritage Agency Geoportal publishes both the official 2D cadastral layer and all heritage datasets. This allows users to overlay and compare protected archaeological zones and monuments with parcel boundaries directly in the web viewer or via WMS/WFS services, even though the cadastre itself does not embed those heritage restrictions.

2.4.3. Greece

Greece protects its cultural heritage under a strong national framework centered on Law 3028/2002 on the Protection of Antiquities and Cultural Heritage, which was updated by Law 4858/2021. This law defines state ownership of antiquities and sets out procedures for the designation and management of archaeological sites, historic places, and immovable monuments. Article 24 of the Hellenic Constitution of 1975 clearly establishes the state's duty to safeguard cultural heritage, providing the constitutional basis for implementation and enforcement [Basiouka, 2024]. Administration lies with the Ministry of Culture, and through the Directorate for the Curation of the National Archive of Monuments which oversees regional Ephorates of Antiquities [Dimopoulou and Gogolou, 2013].

Historically, records of archaeological sites and monuments were spread across paper archives in various Ephorates. Early digital efforts such as "Polemonas" and the "List of Monuments" remained incomplete [Basiouka, 2024]. To address these gaps, the Ministry launched

the Hellenic Archaeological Cadastre (HAC) in 2011 as a national land administration system dedicated to cultural heritage. Completed in 2021, HAC systematically documents and georeferences archaeological sites, buffer zones, immovable monuments, and state-owned properties acquired for archaeological purposes. It stores both spatial and attribute data digitized from historic maps and new field surveys using the EGSA 87 geodetic reference system while its database links each protected area or monument to relevant acts.

According to Basiouka [2024], the HAC has been implemented through several sub-projects, including the digital registration of immovable monuments, the delineation of archaeological sites and their protection zones, and the inventory of state-owned properties acquired for cultural purposes. Although the core database and public geoportal were completed in 2021, important elements remain under development. In particular, the project continues to expand coverage to maritime and underwater heritage and to refine protection-zone boundaries. Attribute data only for public property are cross-checked with the Hellenic Cadastre but this process is currently a manual quality-control procedure rather than a fully automated or continuously synchronized link. Future work aims at deeper interoperability with the National Spatial Data Infrastructure and a more seamless connection to the Hellenic Cadastre to keep the archaeological records consistently up to date.

2.5. Requirements Identification

This section presents a comparative analysis of the three national heritage registers discussed earlier in this chapter drawing on the literature review. Upon examination of their key characteristics, as summarized in Table 2.1, it identifies the main functional and structural aspects that inform the requirements for an archaeological profile based on LADM.

The comparison reveals that the connection between heritage designations and national cadastres is inconsistent. The Netherlands stands out for its formal integration, as heritage restrictions are recorded in the PLR dataset and directly associated with cadastral parcels. In contrast, the Flemish system provides only visual overlays of heritage layers on cadastral maps without a legal link, while the HAC maintains separate records with no direct connection to the national cadastre. This separation of legal and archaeological information, and their maintenance in parallel but disconnected databases, underscores the need for an integrated legal–spatial archaeological model in which every protected object or site is tied not only to its governing act but also to its associated RRR.

A second observation is the absence of true 3D representations of legal spaces. None of the examined registers captures the volumetric extent of protected monuments or underground areas; even in the Netherlands the linkage to parcels remains purely 2D. This confirms a persistent mismatch between the real-world 3D extent of heritage objects and the way they are currently registered.

In addition, the table highlights the absence of standardization. Each system relies on its own data structures and terminology, which constrains interoperability as well as cross-border comparison and data exchange. Establishing a common standard is therefore essential. Because the literature shows that an LADM-based archaeological profile has already been developed for Greece [Dimopoulou and Gogolou, 2013], this research will use that profile as a starting point and backbone for further development, while also extending the approach to the situations in the Netherlands and Belgium.

In general the literature shows that despite significant advances in 3D LAS for modern infrastructure, the unique challenges posed by archaeological sites remain partially unexplored. While the conceptualization and development of 3D LADM-based models for both underground and above-ground spatial units continue to improve and are undeniably fundamental to research in this field, there is a noticeable lack of case studies that integrate point cloud data into these models. Historic areas often contain detailed spatial information that is not typically captured by common encoding models such as BIM/IFC, GML, CityGML, LandXML, and CAD. Instead, much of the data is stored in point cloud formats (e.g., LAS, LAZ), as low-cost and accurate data collection techniques are increasingly adopted in the industry [Voûte et al., 2023].

Based on these observations, three core requirements emerge for the proposed LADM-based archaeological profile:

- an integrated legal–spatial model
- support for 3D representation of legal archaeological spaces using point clouds, and
- standardization through the adoption of internationally recognized standards following existing LADM-archaeological profiles

Country/System	**Managing Authority**	**Scope&Content**	**Linkage to Cadastre**	**Standardization**	**3D Aspects**
The Netherlands / National Monument Register	Dutch Cultural Heritage Agency	Registering all the designated monuments (old and new) and archaeological sites	Yes, through PLR	No	No
Belgium (Flanders) / Flanders Heritage Geoportal	Flanders Heritage Agency	Registering and digitizing protected monuments, archaeological sites, landscapes, UNESCO areas	Available only as overlay layers in the geoportal; no direct linkage to cadastral parcels	No	No
Greece / Hellenic Archaeological Cadastre	Directorate for the Curation of the National Archive of Monuments	Collecting, preserving, digitizing records of mobile and immovable monuments	No, only manual checks for public property identification	No (only conceptualization)	No (only conceptualization)

Table 2.1.: Key features of national monument and heritage registers

3. Methodology

3.1. Research Methodology

This research follows the Design Science Research (DSR) approach of Hevner and Chatterjee [2010]. DSR aims to direct human creativity toward the creation of useful artifacts, focusing on solving important unresolved issues in new or novel ways and improving the effectiveness and efficiency of existing solutions. The approach organizes research into three closely related cycles (Figure 3.1):

- Relevance cycle: connects the research to its environment by identifying the problem and gathering requirements from practice.
- Design cycle: concentrates on building and refining the artifact through iterative design and evaluation.
- Rigor cycle: anchors the work in the scientific knowledge base, drawing on established theories and adding new insights.

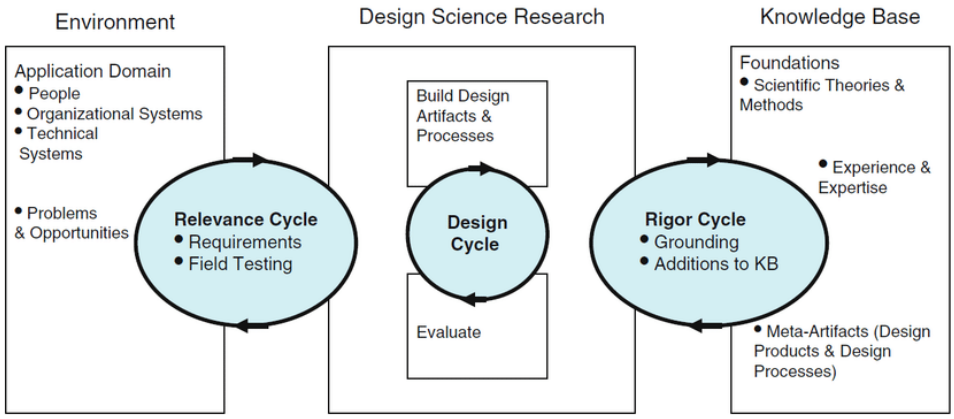


Figure 3.1.: Design Science Research Cycles (Hevner & Chatterjee, 2010)

For the mapping of this approach to the current study, a more detailed explanation of each cycle's function is required. Figure 3.2 presents the interpretation of DSR when the artifact of the research is an LADM-based archaeological profile. This interpretation was also influenced by Kalogianni et al. [2021], which helped identify the specific steps associated with each cycle.

The relevance cycle corresponds to the problem definition achieved through the review of the literature. This process leads to the formulation of the research problem and, ultimately, to the definition of the system requirements. Because the requirements depend both on the

literature and on design considerations, their definition belongs partly to the design cycle as well. The relevance cycle has already been covered in Chapter 2, where the initial set of requirements was established.

Chapter 3 embodies the design cycle, in which those requirements are refined and guide key decisions such as the scope of the profile, the legal framework, the RRR modelling, and the definition of archaeological spatial units.

Finally, the rigor cycle is addressed in both Chapter 4 and Chapter 5, where the conceptual model is presented and subsequently validated through instance-level diagrams, database development and querying, and visualizations.

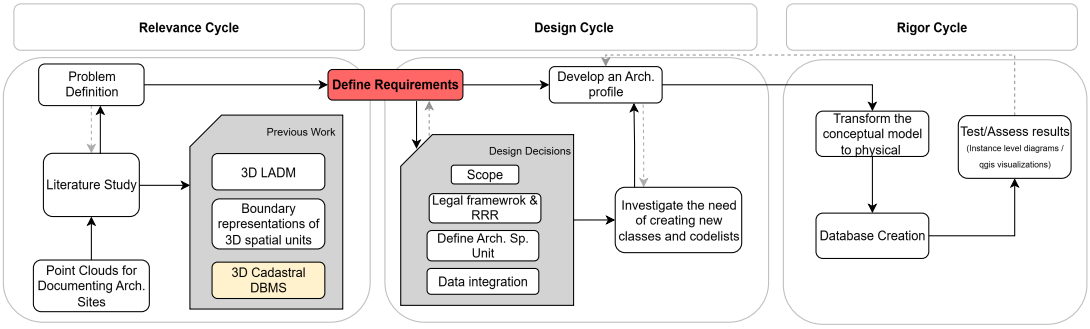


Figure 3.2.: Research Methodology

3.2. Design Decisions

3.2.1. Scope

According to Kalogianni et al. [2021], the developed profiles can be categorized into two groups that relate directly to the scope of the designed profile. Those adopting a holistic approach to modeling land information and those mapping a domain-specific application of land information. As introduced in the previous chapters, this study aims to develop a domain-specific profile. However, simply describing the focused domain is not sufficient to convey the full extent of the scope. Since LADM is a generic flexible standard, the profile must clearly state what types of heritage information it intends to manage, for whom, and how.

This profile focuses exclusively on immovable archaeological or heritage objects and sites, whether on the surface or underground, that have been fully or partially designated as protected heritage. In this thesis the term "archaeological" is used simply to refer to these immovable heritage objects and sites, providing a consistent and convenient label. Choosing this precise thematic focus is a *design decision*, as it determines the classes to be modelled, the legal sources to be referenced, and the spatial representations to be supported within the LADM framework. In its initial stage the model will represent only *legal information*, emphasising the precise linkage of rights, restrictions, and responsibilities to three-dimensional spatial units so that the complete vertical extent of protected areas can be formally recorded. The long-term vision, to be developed in consultation with experts, is to extend the profile to

include scientific and archaeological attributes for richer documentation. The primary purpose of the profile is therefore the legal registration of areas of archaeological interest not only in two dimensions but also as explicit three-dimensional units, ensuring that subsurface remains and volumetric protections are accurately captured within the LADM framework.

3.2.2. Legal Framework & RRRs

A second key design decision concerns the legal framework and the modeling of RRR. Because the proposed profile aims to serve as a legal register for archaeological objects, it must accurately represent how ownership, use, and protective obligations are defined in the relevant jurisdictions and capture those rules in LADM's administrative classes.

Ownership and vertical extent

Civil-law traditions in the Netherlands, Belgium, and Greece recognise that a landowner's rights extend above and below the surface only insofar as useful for exercising ownership, rather than "from the centre of the earth to the heavens." Each country's heritage legislation further limits these vertical rights. In Greece, all antiquities, movable or immovable, belong to the State (Law 3028/2002, Arts. 2–3), eliminating private claims to archaeological remains regardless of depth. Belgium's Civil Code (Art. 552) and the Dutch Civil Code (Book 5, Art. 20) grant ownership of the subsoil only to the extent required for reasonable use, while their heritage laws impose additional public-law constraints.

Based on different legislations examined, the following RRRs were identified as the most crucial ones to be included as instances in the administration package in the developed profile.

Rights

- State ownership of antiquities – Greece: automatic state ownership of all antiquities (Law 3028/2002, Arts. 2–3).
- Ownership of excavation finds – Netherlands: finds from official excavations vest in a public authority unless prior ownership is proven (Erfgoedwet Art. 5.7).
- Use of subsoil for normal exploitation – Belgium and Netherlands: civil-law right to use the subsurface to the extent of reasonable enjoyment (Belgian Civil Code Art. 552; Dutch Civil Code Art. 20).

Restrictions

- Permit or certification for excavation
  - Netherlands: archaeological excavations may only be conducted by certified organizations (Erfgoedwet).
  - Belgium (Flanders): any works on a protected monument, site, or within a protected archaeological zone require prior authorization or specific heritage permit (Onroerenderfgoeddecreet 2013).

  - Greece: construction, excavation, or land-use change within designated archaeological sites or zones requires approval from the Ministry of Culture (Law 3028/2002, Arts. 10–15).

- Mandatory archaeological assessment –Belgium (Flanders): preliminary archaeological research may be imposed as a condition for development permits.

Responsibilities

- Reporting and documentation – Netherlands and Greece: anyone discovering antiquities must report the find to the competent authority.
- Conservation and maintenance duties – owners of listed monuments in all three countries must maintain the property to prevent deterioration, subject to agency oversight (the State most of the times).

Handling Cross-Boundary cases

Some archaeological sites cross international borders, requiring the RRRs of both the affected parcels and the archaeological site itself to be defined according to the legislation of each country. To address this situation, the profile will treat the site as a single archaeological object identified globally, while linking it to separate spatial representations for each jurisdiction. These representations, defined within the LADM spatial package, capture the geometry of the protected area in each country and allow the corresponding RRRs, covering both the parcels and the site as a whole, to be recorded in line with the applicable national legislation. To ensure these geometries align seamlessly across national datasets, the profile will adopt a common Coordinate Reference System (CRS) which guarantees that spatial data from different jurisdictions can be accurately integrated and visualized as a single coherent 3D representation of the site.

3.2.3. Archaeological Unit Definition

In defining the archaeological spatial unit, several conceptual options from 3D cadastre literature were reviewed. One option is to restrict the vertical extent of an existing parcel's rights, treating everything above or below a set depth as outside the owner's domain. Another is to register underground volumes as if they were condominium levels stacked within a parcel. A third is to create a stand-alone "objects registry" for subsurface spaces, entirely independent of the land cadastre. A further possibility is to assign the underground volume to the parcel that provides physical access—for example, where an entrance shaft is located—regardless of the horizontal extent of the remains.

While these approaches can document underground features, they either fail to create explicit restrictions on all affected surface parcels or weaken the legal relationship with the cadastral system.

This study therefore adopts the spatial sub-parcel concept. The archaeological unit is recorded as a distinct 3D basic administrative unit whose geometry is derived from classified point-cloud data but remains linked to the overlying cadastral parcel for reference. Each point in

the cloud is tagged with the parcel's identifier, and the aggregated points form a single volumetric object that receives its own cadastral-style code. This design preserves the ability to trace the archaeological unit back to its surface parcel while registering it as an independent legal entity within the LADM framework, enabling clear assignment of rights, restrictions, and responsibilities to the protected 3D volume.

3.2.4. Temporal Management and Versioning

The LADM provides a mechanism for temporal management through the abstract class *VersionedObject*. This class allows spatial and administrative entities to store version information such as creation and termination dates, enabling the reconstruction of historical states and the tracking of changes over time. Integrating this temporal aspect into a land administration or heritage system is essential for maintaining data consistency, historical traceability, and long-term accountability.

In the developed model, this capability will be adopted to manage the evolution of both spatial and legal information related to archaeological sites. Incorporating versioning ensures that objects within the model are not treated as static entities but can reflect the progression of archaeological knowledge and the dynamic nature of RRR.

This temporal dimension is particularly significant in archaeology, where spatial understanding changes as new discoveries are made or as interpretations evolve. The boundaries of an archaeological unit may expand, contract, or shift as excavations progress, and the legal status of a site may be revised to reflect its updated cultural or scientific importance. By embedding versioning at the conceptual level, the model will be able to document such changes transparently and preserve the relationships between successive states. This approach provides a foundation for future implementations where temporal queries can retrieve past configurations or legal conditions of archaeological spaces.

4. Profile Development

As already mentioned is the previous chapters the LADM is adopted because it supports the creation of detailed administrative and spatial records while offering flexible and scalable methods for representing entities and their semantics. Its structure captures relationships between people and land as well as the particular characterisitcs of property ownerships. As a result, cadastral records can dosument specific parties, legal sources, parcels and property rights involved in each transaction, rather than relying on generic descriptions.

4.1. Core Classes

In this model, the prefix *Arch3D* is used to distinguish the specialized classes developed for this thesis from the core classes of the ISO 19152 LADM Part 2. The design is inspired by previous work of Dimopoulou and Gogolou [2013] about the HAC. The model draws on the principal LADM packages, Party, Administrative, Spatial Unit, and Surveying & Representation as depicted in Figure 4.1.

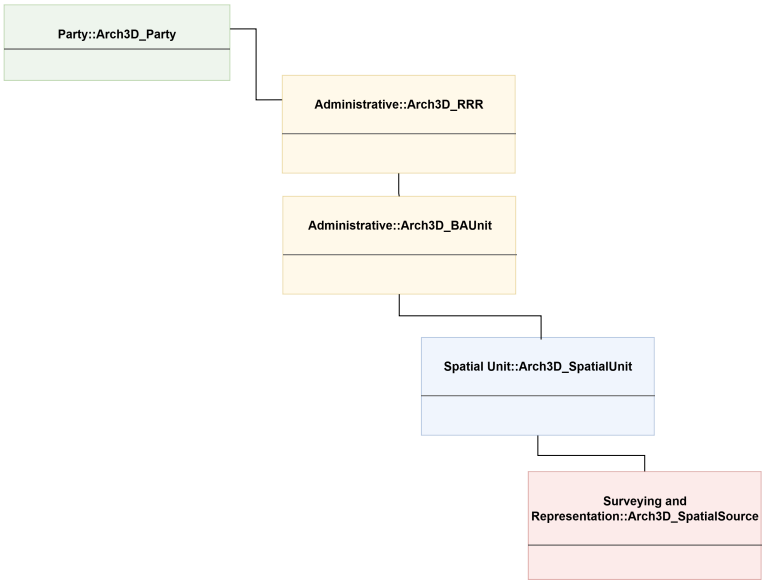


Figure 4.1.: Classes of the proposed model

Party::Arch3D_Party

Represents all actors involved in the archaeological land-administration process, including public heritage agencies, cadastral authorities, private owners of surface parcels, and licensed archaeologists. This class ensures that every RRR can be linked to the people or organizations that hold or enforce it.

Administrative::Arch3D_RRR

Captures the RRRs defined in legislation such as state ownership of antiquities, excavation-permit requirements, or maintenance duties for listed monuments—and links them to the appropriate 3D archaeological units.

Administrative::Arch3D_BAUnit

Defines the Basic Administrative Unit, the legal object to which one or more RRRs apply. Each protected archaeological volume is recorded as its own BAUnit, distinct from but cross-referenced to the overlying 2D cadastral parcel. This separation allows the archaeological space to function as a registrable 3D legal entity while preserving a reference to the surface parcel.

Spatial Unit::Arch3D_SpatialUnit

Describes the three-dimensional geometry of the archaeological unit, derived from classified point-cloud data or other survey sources. It records the complete vertical and horizontal extent of the protected remains so that legal rights and restrictions match the true physical boundaries.

Surveying & Representation::Arch3D_SpatialSource

Documents the measurement data and metadata—such as point-cloud surveys, photogrammetric models, or excavation records—that define each spatial unit and provide the reference systems and quality indicators required for validation and future updates.

4.2. Additional Classes

VersionedObject Superclass
Core classes such as *Arch3D_BAUnit*, *Arch3D_SpatialUnit*, and *Arch3D_RRR* inherit from the VersionedObject superclass. This inheritance provides attributes for life-cycle management (e.g., `beginLifeSpanVersion`, `endLifeSpanVersion`), enabling the model to record successive states of archaeological units as excavations or legal designations change over time—an important requirement in archaeological documentation.

Arch3D_RRR
Arch3D_RRR is an abstract class. An instance of one of its subclasses (*Arch3D_Right*,

Arch3D_Restriction, or *Arch3D_Responsibility*) represents a specific legal right, restriction, or responsibility. This generalisation captures all attributes common to RRRs (e.g., legal source, party link) in a single parent, while allowing each child class to store and manage its own type of legal relationship. Such a structure reflects the LADM principle of separating generic RRR concepts from their specialised legal manifestations and supports clear querying of individual R, R, or R types.

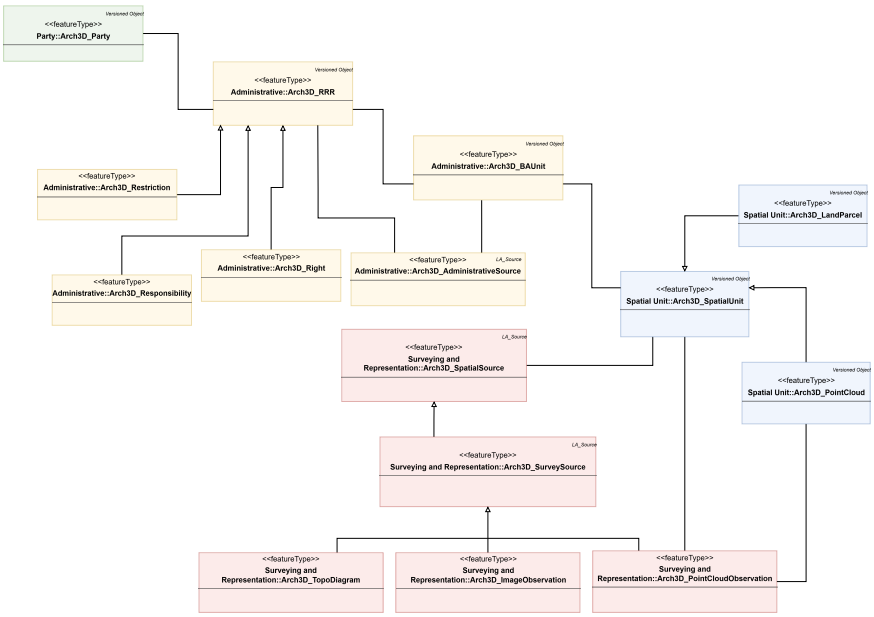


Figure 4.2.: Additional Classes of the proposed model

Arch3D_SpatialUnit
Arch3D_SpatialUnit is an abstract class that provides the common properties of archaeological spatial units. It has two concrete subclasses: *Arch3D_SpatialUnit2D* for surface footprints and *Arch3D_SpatialUnit3D* for volumetric archaeological spaces. This distinction allows the model to handle both traditional 2D parcels and true 3D archaeological volumes while sharing identifiers, versioning, and reference-system attributes. It is essential in archaeology, where new excavations can refine or expand the known vertical extent of a site.

Arch3D_TopoDiagram, Arch3D_ImageObservation, Arch3D_PointCloudObservation
These three classes are concrete subclasses of a common surveying/source abstraction. Each represents a distinct survey input: – *Arch3D_TopoDiagram* for topographic plans, – *Arch3D_ImageObservation* for imagery or aerial photography, and – *Arch3D_PointCloudObservation* for point-cloud measurements. They share metadata attributes for method, date, and accuracy but specialise the observation type, ensuring that all measurement sources used to define an archaeological spatial unit are explicitly recorded and traceable

4.3. Relationships & Multiplicities

This section describes the associations and multiplicities among the classes in the model, using UML terminology and grouping the discussion by LADM package.

Party Package

Arch3D_Party ↔ Arch3D_RRR (Administrative). An *Arch3D_Party* participates in zero or more legal relations (0..∗), and each *Arch3D_RRR* is held by or imposed on one or more parties (1..∗). *Example:* a heritage agency may impose many restrictions; an owner may hold multiple rights; a restriction (e.g., "permit required") typically names at least one competent authority and one obligated party.

Administrative Package

Class `Arch3D_BAUnit` represents a *Basic Administrative Unit* in the Arch3D profile, following the definition in ISO 19152-2 (§7.4.1). A `BAUnit` is the essential administrative object for which one or more RRRs (rights, restrictions, responsibilities) are attached and registered. In the archaeological context it serves as the legal container that links the archaeological spatial units to the administrative and legal information required.

Core role. Each `Arch3D_BAUnit` groups one or more spatial representations of an archaeological site (2D parcels, 3D volumes, or both) that are treated as a single legal unit for the purpose of assigning RRRs. This grouping is valid only when the associated RRRs are unique and homogeneous across all included spatial units—that is, each right, restriction, or responsibility applies in the same way to every spatial component of the BAUnit. Different parties may be involved, but the set of RRRs must remain identical for the BAUnit as a whole. If the RRRs differ, the spatial units must be registered in separate BAUnits.

Associations and multiplicities.

- With `Arch3D_RRR`: A `BAUnit` is associated with (`1..*`) RRR instances, because a basic administrative unit cannot exist without at least one right, restriction, or responsibility. Each `Arch3D_RRR` applies to exactly one `BAUnit` (`1`).
- With `Arch3D_SpatialUnit` (2D or 3D): Each `BAUnit` is linked to (`1..*`) spatial units, ensuring that every BAUnit has at least one geometric representation (2D parcel, 3D volume, or both) while a single `Arch3D_SpatialUnit` may be referenced by one or more BAUnits (`1..*`) when it forms part of multiple administrative groupings.
- With `Arch3D_AdministrativeSource`: One or more administrative sources (`1..*`) provide the legal evidence (such as heritage declarations or official permits) supporting the BAUnit's existence and the attached RRRs.
- With `Arch3D_Party`: Through the `Arch3D_RRR` association, parties such as government agencies, local authorities, or private owners are related to the BAUnit to reflect their RRR.

Interpretation. By grouping the spatial component of an archaeological site and the legal relationships to parties and sources, `Arch3D_BAUnit` provides the pivotal link between the physical archaeological space and the legal registration domain. This structure supports complex scenarios by allowing each BAUnit to maintain a consistent legal identity while its underlying spatial units may change or expand over time.

Spatial Package

The `Arch3D_SpatialUnit` package captures the geometric representation of areas relevant to the archaeological register. It follows ISO 19152-2 by distinguishing between abstract and concrete spatial units, allowing the model to represent both the official 2D cadastral boundary and any protected 3D archaeological volume.

Core structure. `Arch3D_SpatialUnit` is an abstract class that provides common identification, versioning, and reference-system attributes for all spatial representations. It has two subclasses:

- `Arch3D_SpatialUnit2D` – represents the corresponding cadastral parcel. This may coincide with an archaeological designation or simply be the surface parcel that overlies an underground archaeological volume.
- `Arch3D_SpatialUnit3D` – represents the volumetric extent of the protected archaeological remains.

This separation allows the model to register both the legal surface parcel and the three-dimensional protected space, even when the 2D parcel is not itself designated as an archaeological site.

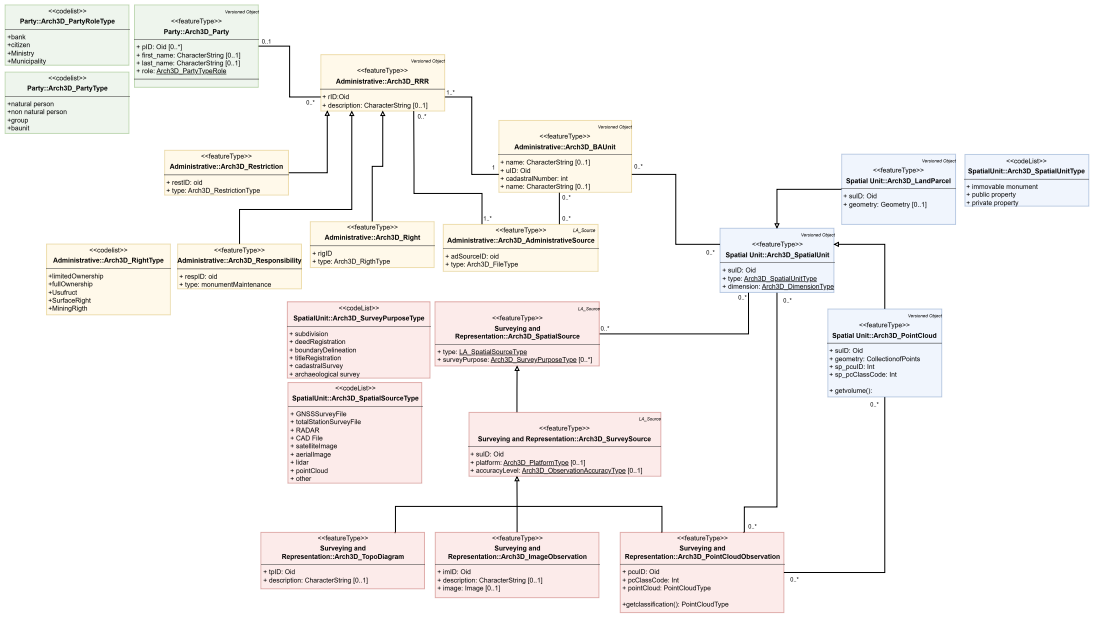


Figure 4.3.: Classes and Relationships of the proposed model

Associations and multiplicities.

- With `Arch3D_PointCloudObservation` (Surveying & Representation): An `Arch3D_SpatialUnit3D` is derived from or validated by one or more point-cloud observations (`1..*`), and an `Arch3D_PointCloudObservation` may support zero or more spatial units (`0..*`). In the research workflow, the classified point cloud is an instance of `Arch3D_PointCloudObservation`;

the collection of points that share the same classification code (e.g., the code inherited from the overlying parcel record) constitutes the geometric basis of a single `Arch3D_SpatialUnit3D`. This association formalises that a spatial unit can be reconstructed from identifiable subsets of an observed point cloud while preserving provenance and reprocessability.

Interpretation. By distinguishing between `Arch3D_SpatialUnit2D` and `Arch3D_SpatialUnit3D`, the model records both the authoritative cadastral parcel used as the 2D legal reference and any 3D archaeological space that requires explicit volumetric representation. Linking `Arch3D_SpatialUnit3D` to `Arch3D_PointCloudObservation` with multiplicity `1..*` ensures that every protected volume is grounded in observable measurements.

5. Evaluation of the proposed model

This chapter evaluates the archaeological profile through practical implementation and testing. It introduces the archaeological datasets used for validation, demonstrates the model at instance level, describes its database implementation and querying, and concludes with visualizations that illustrate how the model supports integrated 3D analysis.

5.1. Case studies

To implement and test the proposed LADM archaeological profile, archaeological site datasets were requested from:

- The Ephorate of Antiquities of region Rhodope in North-East Greece.
- The municipality of Riemst, Belgium.

Byzantine Wall (Urban case): The Byzantine walls of Komotini are the remains of a fortress city built around the early 14th century, following the destruction of the nearby Mosynopolis. Figure 5.1 depicts the 2D geometry of the monument, "monument - polygonal", as registered in the HAC, its condition today and the point cloud.

(a) Monument details in the HAC (b) East side of the wall (c) PC of the west side of the wall

Figure 5.1.: Byzantine Wall (Urban case)

Mosynopolis (Rural case): Mosynopolis, of which only ruins now remain in Greek Thrace, was a city in the Roman province of Rhodope, which was known until the 9th century as Maximianopolis or, to distinguish it from other cities of the same name, as Maximianopolis in Rhodope. Figure 5.2 depicts a central plan church in Mosynopolis, which is the only remaining of the whole area, and the "monument-polygonal" as registered in the HAC.

(a) Monument details in the HAC (b) Remains of the temple (c) PC of the remains

Figure 5.2.: Mosynopolis (Rural case)

Underground Quarries in Riemst (Belgium–Netherlands cross-border case study): The municipality of Riemst is located along the Belgian–Dutch border and forms part of the international Krijtland region, characterized by extensive underground limestone formations. These Cretaceous chalk layers have been quarried for centuries and were widely used as building material across both countries [Lahaye et al., 2022]. The region contains more than 400 known underground quarries, several of which extend across the national border. The underground networks preserve a rich combination of natural, geological, and cultural values, including Late Medieval drawings and inscriptions that document the long history of stone extraction and local craftsmanship. Despite their historical and cultural importance, many of these quarries on the Belgian side remain only partially mapped, and several exhibit stability problems that have caused surface collapses. The cross-border quarries of Riemst, such as Grote Berg and Caestert, represent a shared cultural landscape where coordinated documentation and management are essential [Lahaye and De Kock, 2024]. 5.3 illustrates a 3D view of the point cloud data captured in one of these quarries, which served as the dataset for the cross-border implementation.

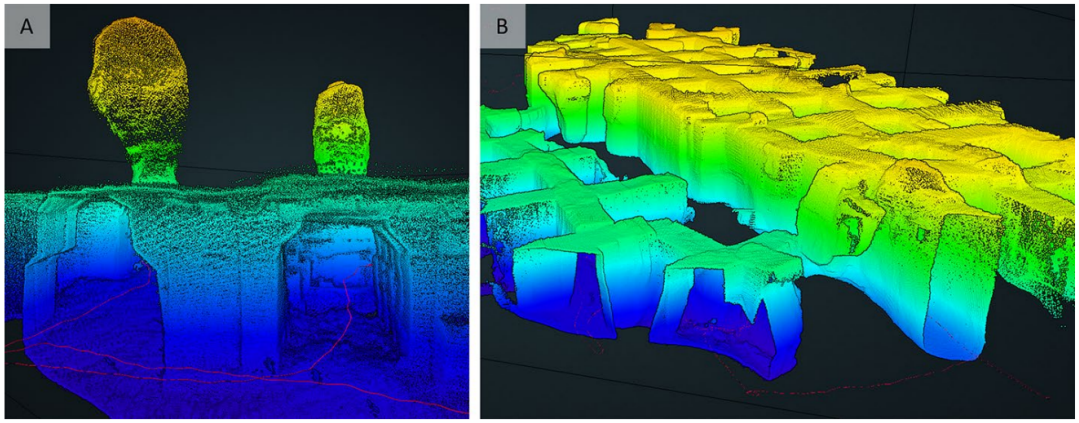


Figure 5.3.: Point cloud of Quarry Grote Berg

5.2. Pre-processing

The point cloud datasets were first manually cleaned to remove outliers and surrounding elements such as vegetation, modern structures, or other objects not considered part of the

archaeological remains. This step ensured that only the geometry relevant to the archaeological features was retained.

A georeferencing step followed where necessary. The datasets from the Greek case studies were already georeferenced in the Hellenic Geodetic Reference System 1987 (EGSA '87). In contrast, the Belgian–Dutch dataset required georeferencing using control points provided by the municipality of Riemst in the ETRS89 / Belgian Lambert 2008 coordinate reference system. According to Lahaye and De Kock [2024], spherical targets were originally used during data acquisition to establish precise control; however, these targets were not visible in the provided point cloud, preventing an exact transformation from the laser scanner's local coordinate system to the Lambert system. As an alternative, a rough alignment was performed manually in CloudCompare by selecting a few reference points distributed near the four corners of the dataset and close to the quarry floor, in order to approximate both the horizontal position and elevation of the point cloud. Although this transformation does not preserve the exact scale or rotation of the original survey, the achieved spatial placement is sufficiently accurate for the purposes of this study, which focuses on conceptual integration rather than metric precision.

5.3. Instance Level Diagrams

Figure 5.2 illustrates two alternative situations in which a 3D archaeological spatial unit lies in a 2D cadastral parcel. In the first case (top part of the diagram), the surface parcel and the 3D archaeological volume are subject to an identical set of rights, restrictions, and responsibilities RRRs. Because these RRRs are unique and homogeneous across both spatial units, they can be registered together within a single `Arch3D_BAUnit`.

In the second case (bottom part of the diagram) the same spatial configuration exists, the 3D archaeological unit is still located in the cadastral parcel but the RRRs differ. For example, the surface parcel may be privately owned while the subsurface archaeological volume is owned or strictly protected by the state. Since the RRRs are no longer identical, the LADM requires two distinct `Arch3D_BAUnit` instances: one representing the surface parcel with its private rights and another representing the archaeological volume with its specific restrictions.

Figure 5.5 illustrates a cross-border situation where an archaeological site extends across cadastral parcels belonging to two different jurisdictions, Belgium and the Netherlands. The same 3D sub-parcel concept described earlier is applied here: instead of representing the entire archaeological site as a single spatial unit, it is divided into separate 3D archaeological units according to the cadastral parcels they intersect. Each of these units is linked to its corresponding parcel and inherits a countryCode descriptor that identifies the jurisdiction in which it lies. This allows the model to manage rights, restrictions, and responsibilities independently for each national segment while maintaining the geometric and semantic continuity of the archaeological site. The country code also enables analytical operations such as calculating the total protected volume within each country or integrating the data into separate national LADM implementations.

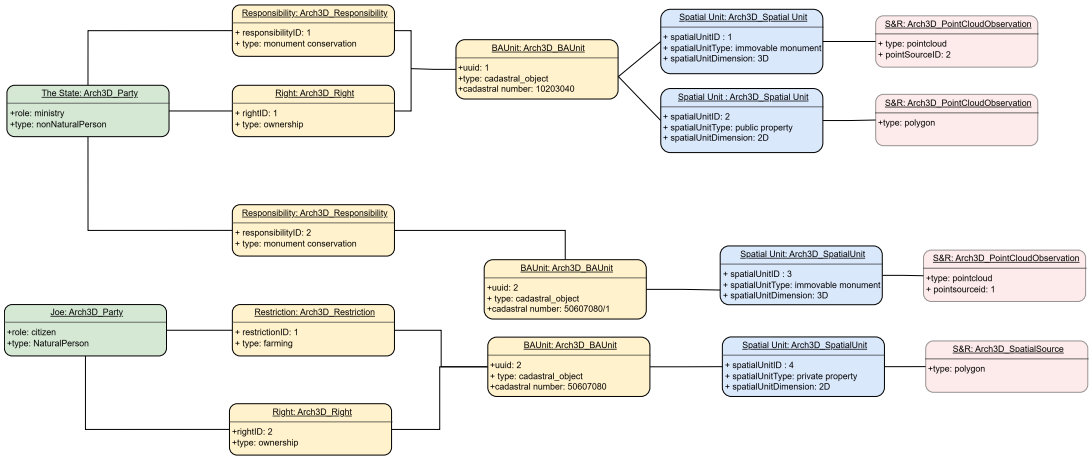


Figure 5.4.: Basic Administrative Unit with two and with one spatial components

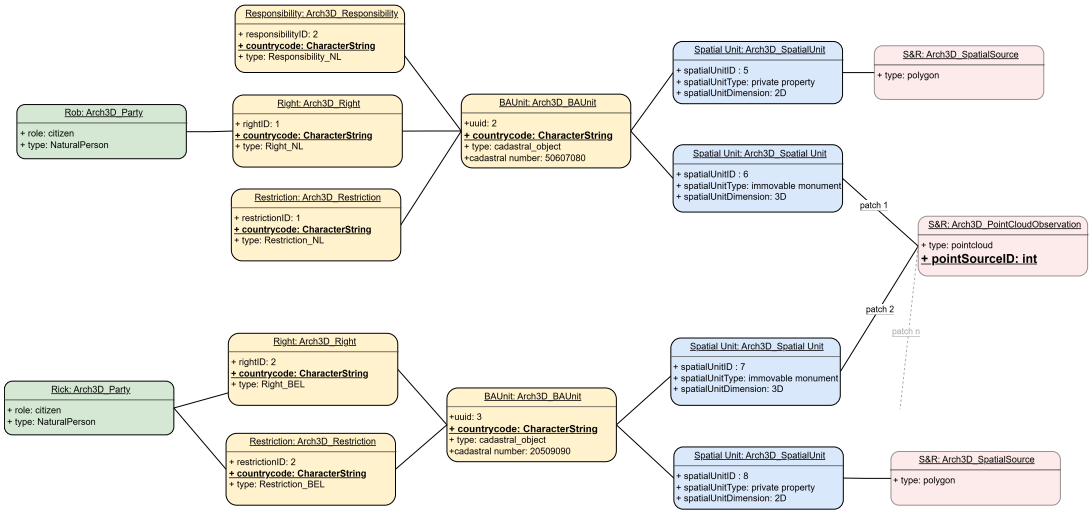


Figure 5.5.: Basic Administrative Units in two different countries

5.4. Database Implementation

The database is implemented in PostgreSQL with the PostGIS extension and follows the Arch3D LADM-based design. The database development of only one of the Greek case studies is presented below while the cross-border case study is not fully described since it's following the same logic with a modification regarding the country code descriptor. All feature tables inherit from `versionedobject`, which provides life-span attributes for temporal versioning. This table provides attributes for both database and real-world versioning, allowing the recording of when an object was created, updated, or became obsolete.

```
CREATE TABLE versionedobject (
    beginlifespanversion TIMESTAMP WITH TIME ZONE,
```

```
    endlifespanversion TIMESTAMP WITH TIME ZONE,
    beginrealworldlifespanversion TIMESTAMP WITH TIME ZONE,
    endrealworldlifespanversion TIMESTAMP WITH TIME ZONE
);
```

5.4.1. Party package

The arch3d_party table stores the actors involved in the management of archaeological spatial units, such as property owners, municipalities, or cultural heritage authorities. Each party is uniquely identified by a UUID (partyid) and can assume one or more roles defined in the arch3d_partyroletype table (e.g., owner, responsible authority, maintainer). This separation of entities and roles allows the model to represent complex administrative relationships where the same actor may have different responsibilities across multiple units.

```
CREATE TABLE arch3d_party (
    pid UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    firstname VARCHAR(100),
    lastname VARCHAR(100),
    role VARCHAR(50)
) INHERITS (versionedobject);
```

5.4.2. Administrative package

The administrative package implements the classes that describe the legal and organizational components of the system, following the structure of the LADM. It includes the tables that represent the basic administrative unit (BAUnit), the RRRs, the related type tables, and the parties involved.

Basic Administrative Unit (BAUnit) table: The arch3d_baunit table represents the fundamental administrative entity in which RRRs are referred to. Each record in the arch3d_baunit table is uniquely identified by a UUID (baunitid), which serves as the primary key. Although the cadastral number would also constitute a natural identifier for a basic administrative unit, a globally unique identifier (UUID) was chosen as the primary key to ensure long-term data integrity and interoperability across systems. Temporal management is inherited from the versionedobject table, allowing the recording of creation and termination dates for each record.

```
CREATE TABLE arch3d_baunit (
    baunitid UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    cadastralnumber VARCHAR(17)
        CHECK (char_length(cadastralnumber) BETWEEN 12 AND 17)
) INHERITS (versionedobject);
```

The constraint was added to maintain consistency with the cadastral numbering convention used in Greece, where cadastral numbers typically consist of 12 to 17 digits. The extended range also accommodates the sub-parcel concept adopted in this research, allowing the registration of 3D archaeological sub-parcels whose identifiers include an additional suffix (e.g.,

"/1", "/2") appended to the base cadastral number. Moreover, this table acts as the administrative link between spatial and legal information. The link between administrative and spatial information is managed through the baunittospatialunit association table. This table allows multiple spatial units to be associated with a single BAUnit and vice versa, enforcing the many-to-many relationship defined in LADM.

```
CREATE TABLE baunittospatialunit (
    baunit UUID REFERENCES arch3d_baunit(baunitid),
    spid UUID REFERENCES arch3d_spatialunit(spatialunitid),
    PRIMARY KEY (baunit, spid)
);
```

Right, Restriction & Responsibility tables: The abstract class RRR from LADM is implemented in the database through three concrete tables: arch3d_right, arch3d_restriction, and arch3d_responsibility. Each of these inherits from the versionedobject table to maintain temporal consistency and includes foreign key references to the corresponding BAUnit and Party. This structure ensures referential integrity and provides version tracking for all administrative relationships.

```
CREATE TABLE arch3d_right (
    rightid UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    baunit UUID REFERENCES arch3d_baunit(baunitid),
    partyid UUID REFERENCES arch3d_party(partyid),
    righttype UUID REFERENCES arch3d_righttype(righttypeid)
);
```

The same structure applies to the arch3d_restriction and arch3d_responsibility tables. To optimize query performance, indexes were created on the foreign key columns of these tables.

```
CREATE INDEX idx_right_baunit ON arch3d_right(baunit);
CREATE INDEX idx_restriction_baunit ON arch3d_restriction(baunit);
CREATE INDEX idx_responsibility_baunit ON arch3d_responsibility(baunit);
```

The codelists of the proposed model are implemented in the database as lookup tables, ensuring that attributes referring to rights, restrictions, and responsibilities use consistent, predefined values. These include the tables arch3d_righttype, arch3d_restrictiontype, and arch3d_responsibilitytype, which act as controlled vocabularies defining the valid categories for each respective class. Each table contains a unique identifier and a short textual description, such as ownership, excavation restriction, or maintenance obligation. This approach enforces data consistency and aligns with the standardized codelist mechanism defined in the LADM.

5.4.3. Spatial Unit package

The spatial unit package includes all areas or volumes that can be linked to administrative information. These are stored in one table, arch3d_spatialunit, which contains both 2D cadastral parcels and 3D archaeological units derived from point cloud data.

```
CREATE TABLE arch3d_spatialunit (
    spatialunitid UUID PRIMARY KEY DEFAULT gen_random_uuid(),
    gid INTEGER,
    kaek VARCHAR(20),
    area NUMERIC,
    geom geometry,
    sputype INTEGER,
    spudimension INTEGER,
    patch INTEGER
) INHERITS (versionedobject);
```

2D parcels have a polygon geometry and an area value, while 3D archaeological units are defined by a patch number that groups the points belonging to the same classified object in the point cloud. The sputype and spudimension fields describe the type and dimension of the unit using coded values. The kaek field stores the cadastral reference number, which links the spatial unit to the cadastral parcel from which it was derived. Although it's a simplified approach, storing both 2D and 3D units in the same table follows the LADM idea that a spatial unit can represent either an area or a volume.

5.4.4. Surveying & Representation Package

The Surveying and Representation package contains the classes that describe the acquisition and representation of spatial data. In this implementation, the arch3d_pointcloudobservation table stores the classified point cloud data used to define the 3D archaeological units.

```
CREATE TABLE arch3d_pointcloudobservation (
    pid SERIAL PRIMARY KEY,
    x NUMERIC,
    y NUMERIC,
    z NUMERIC,
    point_source_id INTEGER REFERENCES arch3d_spatialunit(patch),
    geom geometry(PointZ, 2100)
);

CREATE INDEX idx_pointcloud_geom
ON arch3d_pointcloudobservation
USING GIST (geom);

CREATE INDEX idx_pointcloud_point_source_id
ON arch3d_pointcloudobservation(point_source_id);
```

Each record represents a single point from the classified point cloud, with its 3D coordinates (x, y, z) stored in numeric fields and converted into a geometry object (geom) after import using the ST_MakePoint function. The point_source_id field links each point to the corresponding archaeological unit in the arch3d_spatialunit table through a foreign key referencing the patch attribute. This ensures that all points belong to a valid 3D spatial unit. A spatial index (GiST) was created on the geometry column of the point cloud observation table to support efficient spatial queries. In addition to a spatial index on the geometry column, a standard btree index was added on the point_source_id field. This speeds up queries

that retrieve all points belonging to a specific archaeological unit (i.e. all points with the same patch identifier).

5.4.5. Database Population

The records were inserted manually using SQL in order to populate the tables related to the Party, Administrative packages, and test the relationships defined in the schema. Insertion followed a logical order: first parties and type tables, then BAUnits, then rights, restrictions, and responsibilities. Examples of data insertion for the arch3d_party, the arch3d_baunit, and the arch3d_right are presented.

```
INSERT INTO arch3d_party (beginlifespanversion,
beginrealworldlifespanversion, pid, firstname, role)
VALUES (NOW(), NOW() - INTERVAL '49 years',
gen_random_uuid(), 'Ephorate of Antiquities', 3);
```

```
INSERT INTO arch3d_baunit (beginlifespanversion,
beginrealworldlifespanversion, baunitid, cadastralnumber)
VALUES (NOW(), NOW() - INTERVAL '23years', gen_random_uuid(),
'12345678901234');
```

```
INSERT INTO arch3d_right (beginlifespanversion,
beginrealworldlifespanversion, rightid, righttype, baunit, partyid)
VALUES (NOW(), NOW() - INTERVAL '23years', gen_random_uuid(),2,
'287f3f67-9653-4837-be05-892077f11fb4',
'7a7a70d7-555b-4a13-b746-41ff4eb09154');
```

Regarding the arch3d_spatialunit table, the 2D parcels were imported directly from cadastral shapefiles using the PostGIS tool shp2pgsql and after pre-processing the cadastral parcels enriching them with the desired attributes.

```
shp2pgsql -I -s 2100 cadastral_parcels.shp
arch3d_spatialunit | psql -d arch3d_db
```

This command creates SQL statements to load the shapefile (cadastral_parcels.shp) into the arch3d_spatialunit table using the Greek coordinate reference system EGSA '87 (SRID 2100) and automatically builds a spatial index (-I flag). For 2D parcels, the geom and area attributes were filled, spudimension was set to 2, and patch left empty. For 3D archaeological units, the patch value was filled with the point cloud classification number, spudimension was set to 3, and geom left empty.

For loading the data into the arch3d_pointcloudobservation table, the point cloud was first classified so that each point was assigned to the corresponding cadastral or archaeological spatial unit. As described in Algorithm 5.1, this process checks for each point which spatial unit polygon it lies within and assigns that unit's identifier as its point_source_id.

Algorithm 5.1: Assign cadastral or archaeological unit identifiers to point cloud points

Input: PostGIS database with spatial units $\mathcal{S}$, classified point cloud file P (LAS/LAZ)
Output: Updated point cloud file P' with `point_source_id` assigned

Connect to database;
Establish connection to the PostGIS database;
Retrieve all spatial units from table `arch3d_spatialunit`;
Convert geometries from WKB to polygon objects and create GeoDataFrame $\mathcal{S}$;

Prepare spatial units;
Assign a unique integer label (`class_code`) to each spatial unit in $\mathcal{S}$;
Keep only valid and non-empty geometries;

Load point cloud;
Read LAS/LAZ file P from disk;
Extract coordinates (x, y, z) and create GeoDataFrame of points $\mathcal{P}$;
Ensure $\mathcal{P}$ and $\mathcal{S}$ share the same coordinate reference system;

Spatial join (point-in-polygon);
For each point $p_i \in \mathcal{P}$;
    Find spatial unit $s_j \in \mathcal{S}$ such that $p_i \in s_j$;
    If such s_j exists, assign p_i.`class_code` $\leftarrow$ s_j.`class_code`;
Store matches in a join table (p_i, s_j);

Update point attributes;
For all matched points p_i;
    Overwrite p_i.`point_source_id` $\leftarrow$ p_i.`class_code`;

Write updated point cloud;
Replace `point_source_id` field in LAS object with new values;
Export updated point cloud as P' (LAS/LAZ format);

return *P' with points assigned to corresponding spatial unit identifiers*

The resulting classified point cloud was exported to a CSV file containing the coordinates (x, y, z) and the assigned point_source_id. The file was then imported into the database using the COPY command, which allows efficient bulk loading of large datasets into PostgreSQL.

```
COPY arch3d_pointcloudobservation (x, y, z, point_source_id)
FROM '/path/to/classified_points.csv'
DELIMITER ',' CSV HEADER;
```

After importing the data, the geometry column was created inside PostGIS using the ST_MakePoint function and the coordinate reference system EGSA '87 (SRID 2100).

```
UPDATE arch3d_pointcloudobservation
SET geom = ST_SetSRID(ST_MakePoint(x, y, z), 2100);
```

After the completion of the data insertion process, the resulting tables in the database were populated with records representing both the administrative and spatial components of the model. The next figures below present examples of the populated tables, while the last one (Figure **??**) depicts a general overview of the database.

```
SELECT
    p.*,
    r.prtdescription
FROM arch3d_party AS p
JOIN arch3d_partyroletype AS r
ON p.role = r.prtid;
```

Data Output | Messages | Notifications

Showing rows: 1 to 5 | Page No: 1 of 1

	beginlifespanversion timestamp with time zone	endlifespa timestamp	beginrealworldlifespanversion timestamp with time zone	endrealworl timestamp v	pid uuid	firstname character varying (255)	lastname character varying (255)	role integer	prtdescription character varying (255)
1	2025-06-02 13:24:05.345435+02	[null]	1975-06-02 13:24:05.345435+01	[null]	8480865e-6cb2-...	John	West	2	citizen
2	2025-06-02 13:26:49.786278+02	[null]	1985-06-02 13:26:49.786278+02	[null]	64d00db9-fda7-...	Mark	East	2	citizen
3	2025-06-02 13:32:43.63244+02	[null]	2000-06-02 13:32:43.63244+02	[null]	e0259571-a761-...	Walter	South	2	citizen
4	2025-06-02 13:37:50.966216+02	[null]	1990-06-02 13:37:50.966216+02	[null]	a2bf5b17-2679-...	Tony	Mel	2	citizen
5	2025-06-02 14:00:39.249386+02	[null]	1976-06-02 14:00:39.249386+01	[null]	7a7a70d7-555b-...	Ephorate of Antiquties	Ephorate of Antiquities	3	Ministry

Figure 5.6.: Arch3d_party table included the party role description

```
select * from arch3d_baunit
```

Data Output | Messages | Notifications

Showing rows: 1 to 6 | Page No: 1 of 1

	beginlifespanversion timestamp with time zone	endlifespanversion timestamp with time zone	beginrealworldlifespanversion timestamp with time zone	endrealworldlifespanversion timestamp with time zone	bauunitid [PK] uuid	cadastralnumber character varying (17)
1	2025-05-30 15:29:35.843208+02	[null]	2002-05-30 15:29:35.843208+02	[null]	287f3f67-9653-4837-be05-892077f11fb4	420361722070
2	2025-05-30 15:33:28.064279+02	[null]	2002-05-30 15:33:28.064279+02	[null]	c46f59f6-e4c8-41cc-b2d2-f6933b27411b	420361722033
3	2025-05-30 15:33:56.549961+02	[null]	2002-05-30 15:33:56.549961+02	[null]	f950cbed-96f6-4c0b-80b2-a88a96d509...	420361722068
4	2025-05-30 15:34:22.110177+02	[null]	2002-05-30 15:34:22.110177+02	[null]	dae53bec-9de5-46c5-abee-bd6aee84fa...	420361722143
5	2025-05-30 15:35:14.642453+02	[null]	2002-05-30 15:35:14.642453+02	[null]	f30fd29a-8081-45ed-91d9-ceeaad1a57...	420361722071
6	2025-09-19 18:43:35.038802+02	[null]	2002-09-19 18:43:35.038802+02	[null]	18ee182c-63c3-4b5a-8d29-5b5777c2f2fe	420361722033/1

Figure 5.7.: Arch3d_baunit table

```
select * from arch3d_right
```

Data Output | Messages | Notifications

Showing rows: 1 to 6 | Page No: 1 of 1

	beginlifespanversion timestamp with time zone	endlifespanversion timestamp with time z	beginrealworl timestamp wit	endrealworldlifespanversion timestamp with time zone	rightid [PK] uuid	righttype integer	baunit uuid	partyid uuid
1	2025-06-02 14:50:13.445168+02	[null]	2002-06-0...	[null]	54184790-7f...	2	287f3f67-9653-4837-be05-892077f11fb4	7a7a70d7-555b-4a13-b746-41ff4eb09154
2	2025-06-04 12:40:55.817952+02	[null]	2005-06-0...	[null]	e3c71d92-21...	2	c46f59f6-e4c8-41cc-b2d2-f6933b27411b	a2bf5b17-2679-4620-8225-1781b4ed7e...
3	2025-06-05 17:47:08.86338+02	[null]	2005-06-0...	[null]	d80b3db6-54...	2	f950cbed-96f6-4c0b-80b2-a88a96d509...	e0259571-a761-4300-ac3f-70ee853b60...
4	2025-06-05 17:49:03.004627+02	[null]	2005-06-0...	[null]	5fca3eea-bd...	2	dae53bec-9de5-46c5-abee-bd6aee84fa...	64d00db9-fda7-4908-b4fa-b90cc630913c
5	2025-06-05 17:50:18.71922+02	[null]	2005-06-0...	[null]	3a54fea0-2f3...	2	f30fd29a-8081-45ed-91d9-ceeaad1a57...	8480865e-6cb2-4b91-8cf9-2123ef484eb1
6	2025-09-19 19:01:33.635289+02	[null]	2002-09-1...	[null]	a110e406-09...	2	18ee182c-63c3-4b5a-8d29-5b5777c2f2fe	7a7a70d7-555b-4a13-b746-41ff4eb09154

Figure 5.8.: Arch3d_right table

```
select * from arch3d_spatialunit
```

Data Output | Messages | Notifications

Showing rows: 1 to 7 | Page No: 1

	gid integer	kaek character varying (14)	area numeric	geom geometry	spatialunitid [PK] uuid	sputype integer	spudimension integer	patch integer
1	16	420361722033	26967.279999999998836	0106000020340800000100000000...	720a43e8-22fd-41c6-8a26-6803b9e27af4	3	2	[null]
2	22	420361722070	2000.059999999999945	0106000020340800000100000000...	b6a64501-5326-4b40-b252-d19e15c85edf	3	2	[null]
3	21	420361722068	4000.199999999999818	0106000020340800000100000000...	ffe09c3c-f6d4-4e8a-83f0-3d3c16b0a994	3	2	[null]
4	25	420361722143	4499.979999999999563	0106000020340800000100000000...	30e919ba-c4bf-4724-980c-5c62c4e423f4	3	2	[null]
5	26	420361722071	3703.880000000000109	0106000020340800000100000000...	ec767426-7006-4bda-b4ae-057d5212ee...	3	2	[null]
6	102	420361722070/1	[null]	[null]	e571c84a-0820-438c-9661-345f8725bfb9	1	3	2
7	103	420361722033/1	[null]	[null]	d474dd84-2ae8-4b51-97d2-808892f36746	1	3	1

Figure 5.9.: Arch3d_right table

```
1  select * from arch3d_pointcloudobservation limit 10
```

Data Output | Messages | Notifications

Showing rows: 1 to 10 | Page

	pid [PK] integer	x numeric	y numeric	z numeric	point_source_id integer	geom geometry
1	1	611090.553220	4553600.327150	46.868330	1	01010000A034080000DFA63F1B25A622418E06F014E05E51415E11FC6F256F4740
2	2	611090.364260	4553602.135130	46.311330	1	01010000A034080000664980BA24A622414DF8A588E05E5141C02154A9D92747...
3	3	611089.059080	4553604.026120	46.797330	1	01010000A034080000D8BB3F1E22A6224138F3AB01E15E5141520FD1E80E6647...
4	4	611089.044920	4553604.049130	46.826330	1	01010000A03408000016C1FF1622A6224128F22403E15E514112DA722EC5694740
5	5	611089.933110	4553603.960140	46.589330	1	01010000A0340800000B98C0DD23A622410BEF72FDE05E51419D465A2A6F4B47...
6	6	611090.607910	4553601.940120	46.178330	1	01010000A034080000C2FA3F3725A6224114ED2A7CE05E5141A6F27684D31647...
7	7	611090.372070	4553601.789120	46.266330	1	01010000A03408000084F57FBE24A622412CF18072E05E5141CBF8F71917224740
8	8	611090.849120	4553604.366150	47.119330	1	01010000A0340800004DDBBFB225A6224169006F17E15E514141B79734468F4740
9	9	611090.188960	4553602.750120	46.341330	1	01010000A034080000795DBF6024A6224151F701B0E05E5141649291B3B02B4740
10	10	611090.987300	4553601.565120	46.145330	1	01010000A034080000B7627FF925A6224114ED2A64E05E51415890662C9A124740

Figure 5.10.: Arch3d_pointcloudobservation table

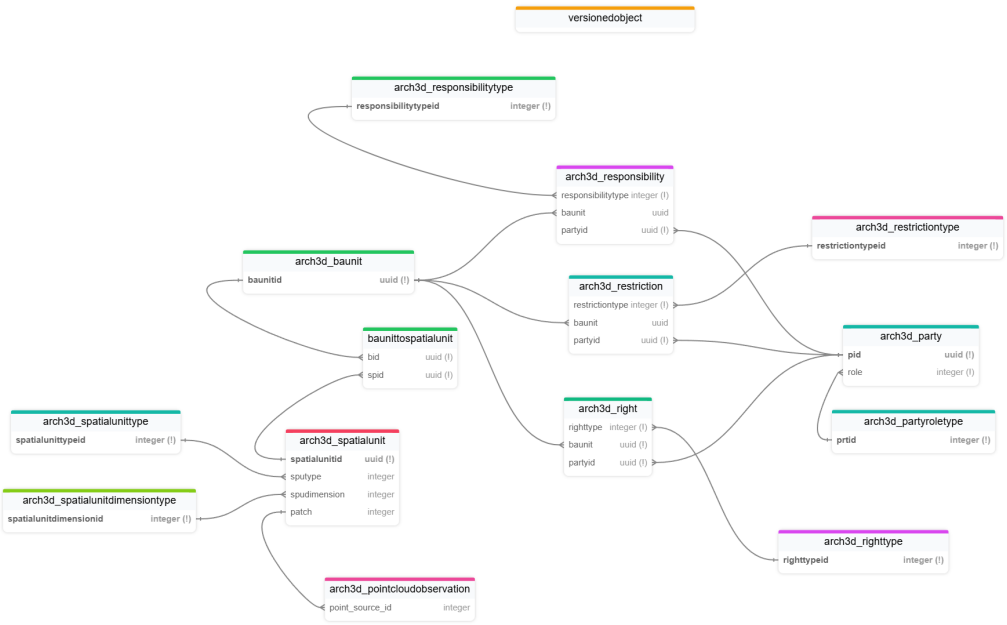


Figure 5.11.: LADM Database Structure

5.5. Queries

A set of SQL queries was executed to verify that the implemented database correctly links administrative, spatial, and point cloud data, and supports the retrieval of legal and archaeological information.

Unified Retrieval of Rights, Restrictions, and Responsibilities

The query below demonstrates how the database integrates the three types of legal relationships defined in the LADM into a single unified view. By combining the corresponding tables through the UNION ALL operator, the query retrieves for each BAUnit the parties involved, the type of RRR, and its description. This consolidated output confirms that the administrative structure functions correctly, allowing a single query to list all legal associations related to each unit.

```
SELECT
    p.firstname AS PartyFirstName,
    p.lastname AS PartyLastName,
    'Right' AS rrr_type,
    rt.rightdescription AS rrr_description,
    b.cadastralnumber AS baunit_cadastral_number,
    b.baunitid
FROM arch3d_party p
JOIN arch3d_right r ON p.pid = r.partyid
JOIN arch3d_righttype rt ON rt.righttypeid = r.righttype
JOIN arch3d_baunit b ON r.baunit = b.baunitid

UNION ALL

SELECT
    p.firstname,
    p.lastname,
    'Restriction' AS rrr_type,
    rst.restrictiondescription AS rrr_description,
    b.cadastralnumber,
    b.baunitid
FROM arch3d_party p
JOIN arch3d_restriction rn ON p.pid = rn.partyid
JOIN arch3d_restrictiontype rst
    ON rst.restrictiontypeid = rn.restrictiontype
JOIN arch3d_baunit b ON b.baunitid = rn.baunit

UNION ALL

SELECT
    p.firstname,
    p.lastname,
    'Responsibility' AS rrr_type,
    rsp.responsibilitydescription AS rrr_description,
    b.cadastralnumber,
    b.baunitid
FROM arch3d_party p
JOIN arch3d_responsibility res ON p.pid = res.partyid
JOIN arch3d_responsibilitytype rsp
    ON rsp.responsibilitytypeid = res.responsibilitytype
JOIN arch3d_baunit b ON b.baunitid = res.baunit;
```

The results show all parties and their associated rights, restrictions, and responsibilities per spatial unit.

	partyfirstname character varying (255)	partylastname character varying (255)	rrr_type text	rrr_description character varying (255)	baunit_cadastral_number character varying (17)	baunitid uuid
1	Ephorate of Antiquties	Ephorate of Antiquities	Right	full ownership	420361722033/1	18ee182c-63c3-4b5a-8d29-5b5777c2f...
2	John	West	Right	full ownership	420361722071	f30fd29a-8081-45ed-91d9-ceeaad1a57...
3	Mark	East	Right	full ownership	420361722143	dae53bec-9de5-46c5-abee-bd6aee84fa...
4	Walter	South	Right	full ownership	420361722068	f950cbed-96f6-4c0b-80b2-a88a96d509...
5	Tony	Mei	Right	full ownership	420361722033	c46f59f6-e4c8-41cc-b2d2-f6933b2741...
6	Ephorate of Antiquties	Ephorate of Antiquities	Right	full ownership	420361722070	287f3f67-9653-4837-be05-892077f11fb4
7	Tony	Mei	Restriction	urban plan constraint	420361722033	c46f59f6-e4c8-41cc-b2d2-f6933b2741...
8	Ephorate of Antiquties	Ephorate of Antiquities	Responsibility	monument conservation	420361722070	287f3f67-9653-4837-be05-892077f11fb4

Figure 5.12.: Query 1

Deriving 2D footprints and the vertical extent of the 3D spatial unit

The following query demonstrates how the database integrates point cloud observations with the spatial and administrative components of the model. It retrieves each 3D spatial unit together with its administrative information, type, and dimensional classification. For each unit, the 2D convex hull of the associated points is computed as an approximate footprint, and the minimum and maximum elevation values (zmin, zmax) define its vertical extent. This illustrates how spatial units can be dynamically derived and analyzed from the classified point cloud data stored in the database.

```
SELECT
    s.gid,
    s.spatialunitid,
    s.patch,
    b.baunitid,
    b.cadastralnumber,
    t.typedescription AS spatialunit_type,
    d.dimensiondescription AS spatialunit_dimension,
    h.zmin,
    h.zmax,
    'hull_from_points'::text AS footprint_source,
    ST_Multi(h.hull_2d)::geometry(MultiPolygon, 2100) AS geom
FROM arch3d_spatialunit AS s
JOIN baunittospatialunit AS bs ON bs.spid = s.spatialunitid
JOIN arch3d_baunit AS b ON b.baunitid = bs.bid
JOIN arch3d_spatialunittype AS t ON t.spatialunittypeid = s.sputype
JOIN arch3d_spatialunitdimensiontype AS d
    ON d.spatialunitdimensionid = s.spudimension
JOIN (
    SELECT
        s2.spatialunitid,
        ST_ConvexHull(ST_Force2D(ST_Collect(p.geom))) AS hull_2d,
        MIN(ST_Z(p.geom)) AS zmin,
        MAX(ST_Z(p.geom)) AS zmax
    FROM arch3d_spatialunit AS s2
    JOIN gr_temple_class AS p ON p.point_source_id = s2.patch
    JOIN arch3d_spatialunitdimensiontype AS d2
        ON d2.spatialunitdimensionid = s2.spudimension
    WHERE d2.dimensiondescription = '3D'
    GROUP BY s2.spatialunitid
) AS h
```

```
ON h.spatialunitid = s.spatialunitid;
```

The query produces one record per 3D archaeological spatial unit, showing its cadastral reference, spatial type, dimension, and computed footprint geometry. The zmin and zmax values describe the vertical range of the archaeological volume, while the 2D convex hull represents its horizontal extent. The results confirm that the model successfully links classified point cloud data with the rest of the tables.

	gid integer	spatialunitid uuid	patch integer	baunitid uuid	cadastralnumber character varying (17)	spatialunit_type character varying (255)	spatialunit_dimension character varying (255)	zmin double precision	zmax double precision	footprint_source text	geom geometry
1	103	d474dd84-2ae...	1	18ee182c-...	420361722033/1	immovable monument	3D	44.76833	49.231	hull_from_points	0106000020340800000100000001030...
2	102	e571c84a-082...	2	287f3f67-9...	420361722070	immovable monument	3D	44.36533	49.486	hull_from_points	0106000020340800000100000001030...

Figure 5.13.: Query 2

5.6. Visualizations

Figure 5.14 presents the visualization of the Greek case study, where both cadastral parcels (in blue and green) and derived archaeological volumes (in yellow and pink) are displayed. The 3D spatial units were generated from the classified point cloud by using the minimum and maximum elevation values (zmin and zmax) obtained from the database query. These volumetric representations provide a clear depiction of the archaeological sub-parcels, allowing the underlying point cloud to be viewed within defined spatial boundaries. The approach illustrates how the 3D archaeological units, defined as collections of classified points, can be effectively visualized and related to the overlying cadastral framework.

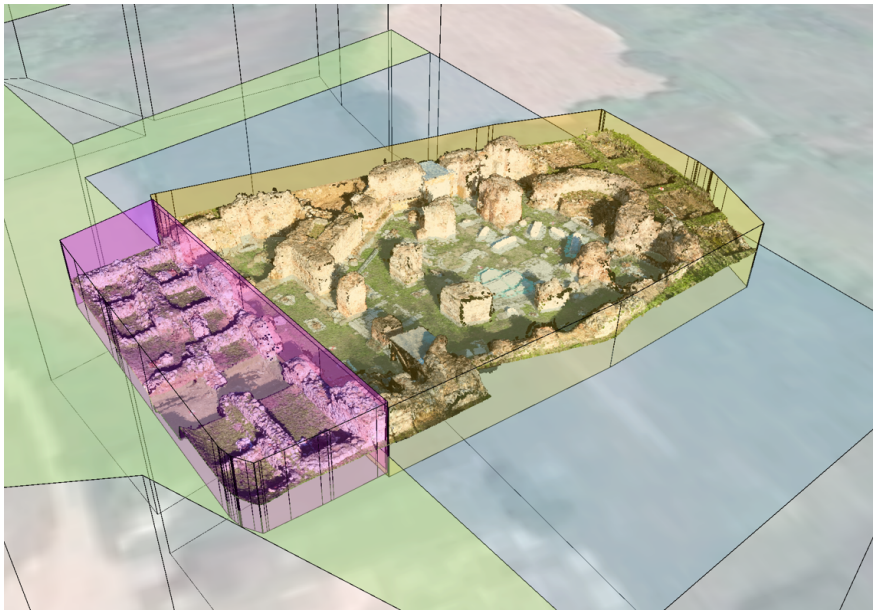


Figure 5.14.: Visualization of the rural Greek case study showing cadastral parcels (blue and green) and corresponding 3D archaeological volumes (yellow and pink).

Figure 5.15 presents the Dutch–Belgian case study. In the map, cadastral parcels from both the Netherlands (outlined in red) and Belgium (outlined in blue) were re-projected to a common coordinate reference system (ETRS89 / EPSG:3035) to ensure spatial compatibility. This harmonized projection allowed the underground quarries displayed as colored volumes and grouped by their associated Spatial Unit to be accurately identified and overlaid across the national boundary.

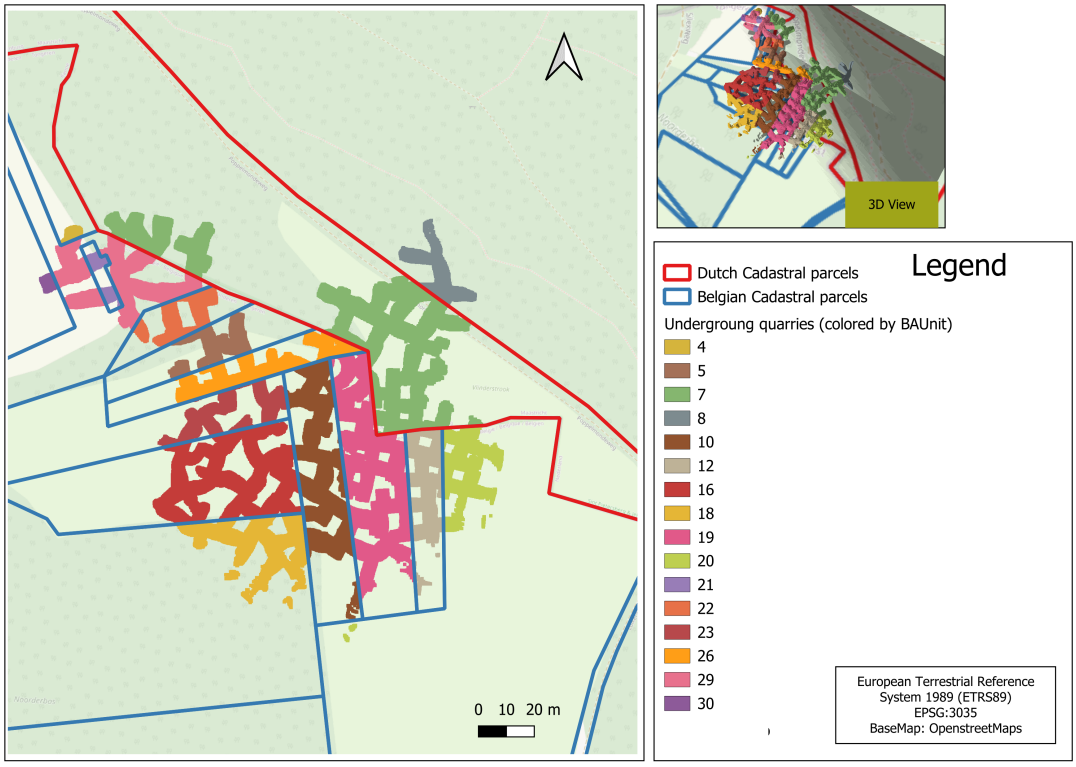


Figure 5.15.: Parcel-based classification for 3D Archaeological Spatial Units Identification

Figure 5.16 presents the 3D visualization of the Dutch–Belgian case study. The underground quarries, represented as volumetric archaeological units, are visualized beneath the cross-border cadastral parcels. The upper surfaces correspond to the overlying parcels.

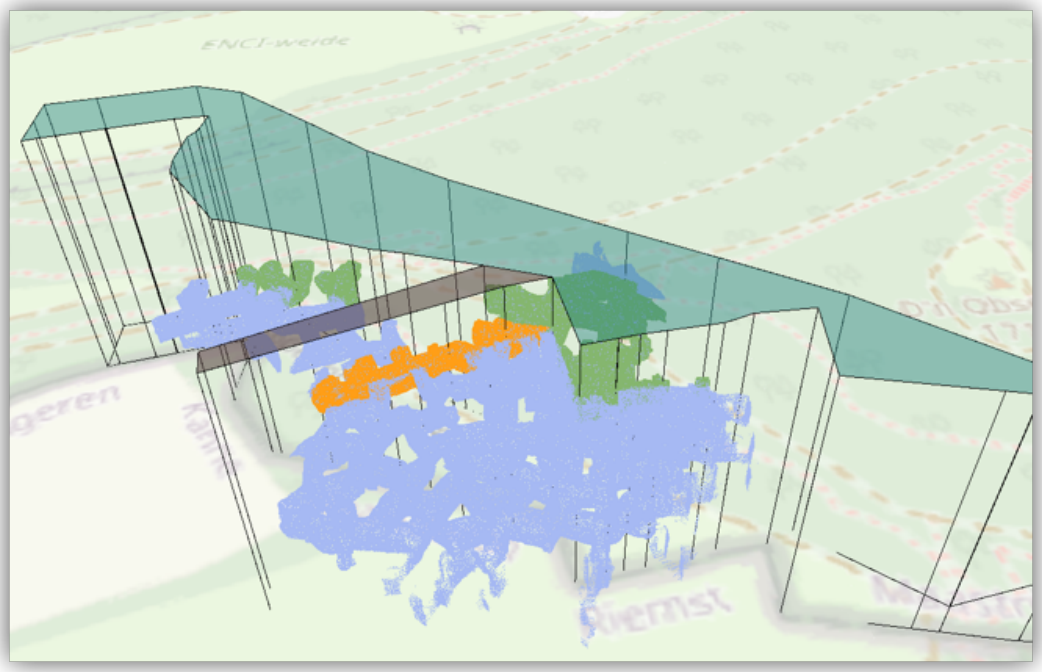


Figure 5.16.: 3D visualization of the cross-border case study

6. Conclusions and Discussion

6.1. Concluding Remarks

This thesis investigated how point cloud data can be integrated into the Land Administration Domain Model (LADM) for archaeological applications, aiming to support 3D representation and documentation of legal and spatial aspects of cultural heritage sites. The work introduced and implemented the Arch3D profile, a prototype extension of LADM tailored to archaeological information and designed to represent spatial units, boundary geometries, and related rights, restrictions, and responsibilities (RRRs).

The main research question, *How can point cloud data be processed so that they can serve as boundary representations within LADM-based applications for archaeological purposes?*, was addressed through the design and partial implementation of the Arch3D model. The research demonstrated that point clouds have the potential to support the spatial representation of archaeological features within an LADM-based structure, where they are treated as isolated archaeological units without following the concept of shared boundaries.

The first sub-question, regarding the development of an LADM archaeological profile, was answered through the creation of the Arch3D classes and their mapping to existing LADM classes. The profile introduces classes such as Arch3D_SpatialUnit, which extend core LADM concepts to include archaeology-related RRRs while maintaining compliance with ISO 19152.

The second sub-question, concerning the selection of boundary patches from point cloud data for use in archaeological applications, was addressed through the adopted definition of the archaeological unit as a three-dimensional sub-parcel. In this approach, boundary patches are obtained by classifying the point cloud data according to the cadastral parcel within or above which each point lies. The aggregated classified points form a volumetric representation of the archaeological unit that remains linked to the overlying parcel. This method allows the resulting 3D unit to be registered as an independent spatial object within the LADM framework while maintaining its legal reference to the corresponding surface parcel.

The third sub-question, which asked how legal and semantic information can be linked with point clouds for archaeological purposes in the context of the LADM, was addressed through the way the data model relates spatial units to legal attributes. In the proposed approach, individual points in the point cloud are associated with an archaeological spatial unit. This spatial unit is then modeled as an object within the Arch3D profile that can carry, or be related to, legal and semantic information such as protection status, responsible authority, and applicable rights, restrictions, and responsibilities.

The fourth sub-question, which focused on structuring and visualizing point cloud–based boundary representations, was partially addressed. Querying functionalities were successfully implemented within the database, allowing the retrieval of archaeological units together with their related legal and semantic information. Validation was carried out partly

through these database queries and the accompanying instance-level diagrams, which confirmed the internal consistency of the model. Visualization was achieved through a semi-automated workflow that converts queried spatial data into volumetric representations using external visualization tools but it is still weak. While this approach demonstrates the potential for linking database content with 3D visualization environments, a direct and fully automated front-end was not developed within this research. Consequently, the outcome represents a conceptual and technical prototype, demonstrating the feasibility of integrating point cloud data and legal semantics within an LADM-compliant framework.

6.2. Discussion

The development of the Arch3D profile showed that the Land Administration Domain Model (LADM) can be effectively adapted to describe archaeology-related spatial units. The model extends LADM's existing structure to represent these units and their related RRRs. This confirms that the standard, although originally designed for land administration, can also serve as a bridge between legal and cultural heritage domains.

From a technical point of view, the implementation proved that point clouds can be linked with legal and semantic information. The use of classified point cloud data to define archaeological sub-parcels enabled the creation of three-dimensional representations that remain connected to their surface parcels. While the workflow remains partly manual, it demonstrates how point cloud information can be integrated into an LADM-compliant database and retrieved through standard queries.

The work also emphasized the value of standardization and interoperability. Archaeological information is often fragmented across different systems and institutions. Using an international standard such as LADM promotes data consistency and opens opportunities for cross-domain collaboration between cadastral and heritage organizations. The model provides a clear framework for storing spatial, legal, and descriptive information together, making archaeological data easier to maintain and exchange.

The cross-border case study between Belgium and the Netherlands also underlined the importance of managing multi-jurisdictional contexts in 3D land administration and heritage documentation. Differences in legal systems, data models, and cadastral practices make cross-border interoperability a significant challenge. In the current prototype, this aspect is handled through a simple countryCode descriptor, which allows each spatial unit and administrative record to retain its national identity. Although this mechanism provides basic differentiation between jurisdictions, more advanced methods for harmonizing data structures and legal semantics will be required to support consistent cross-border registration in future implementations.

Although an approximate georeferencing was sufficient for the purposes of this study, the importance of spatial accuracy must be emphasized when such models are applied in operational land administration contexts. Precise georeferencing is essential to ensure that spatial units are correctly positioned in relation to cadastral parcels and neighboring properties. Inaccuracies in location or elevation could lead to misinterpretation of legal boundaries, overlapping rights, or unintended implications for land use and property management. Therefore, while this research focused on demonstrating the conceptual feasibility of integrating point cloud data into an LADM-based structure, any future operational implementation should ensure rigorous geodetic control and verification of spatial datasets.

At the same time, the research highlighted that extending LADM to a specialized field such as archaeology requires balancing technical accuracy with practical usability. The prototype confirms that LADM can structure archaeological data effectively, but further work is needed to make such systems operational and accessible to end users. Although expert consultation did not take place within the scope of this research, it remains an essential next step to ensure that the model reflects real-world workflows, data requirements, and institutional practices. Overall, this study demonstrates the potential of using LADM and point cloud data for more transparent and integrated heritage documentation.

6.3. Limitations and Future Work

This research was carried out as a prototype and, as such, several limitations should be acknowledged. Three case studies were initially planned: two located in Greece and one cross-border case between Belgium and the Netherlands. Of these, two were implemented — one of the Greek case studies and the Belgian/Dutch one. However, only the Greek case study was fully tested and analyzed in detail, while the Belgian/Dutch implementation was mainly used to assess the cross-border applicability of the proposed model. The web-based visualization was not developed, and the validation of the model was limited to internal database queries and instance-level diagrams. Expert consultation and stakeholder evaluation were not conducted, which limits the assessment of the model's practical relevance.

While versioning was introduced both conceptually and within the database implementation, no practical examples were developed to demonstrate or evaluate its functionality. These gaps define the current system as a technical and conceptual prototype rather than an operational platform.

Future work should focus on completing a detailed evaluation of all case studies, including engagement with heritage and cadastral institutions. The versioning component should be further developed and tested with real examples to confirm its effectiveness in managing temporal changes in archaeological and cadastral data. Developing a direct 3D visualization interface would also enhance accessibility for users and stakeholders. Finally, legal and organizational validation should be pursued to test how the Arch3D profile could be integrated into existing heritage and cadastral infrastructures.

A. Reproducibility self-assessment

A.1. Marks for each of the criteria

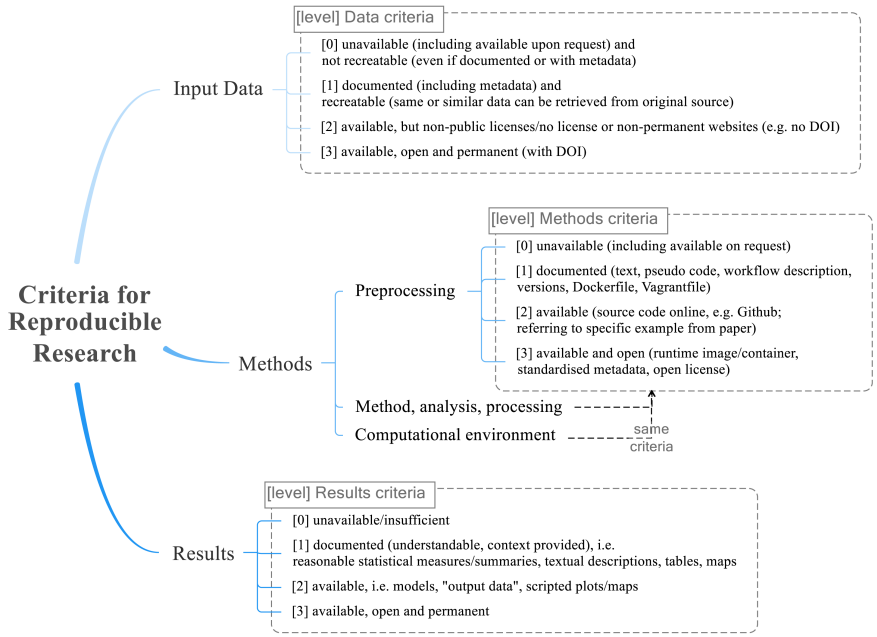


Figure A.1.: Reproducibility criteria to be assessed.

Grade/evaluate yourself for the 5 criteria (giving 0/1/2/3 for each):

1. input data: 0 for point cloud data from archeological sites and 3 for the Greek, Dutch, and Belgian cadastral parcels

2. preprocessing: 1

3. methods: 2

4. computational environment: 1

5. results: 1

A.2. Self-reflection

The datasets used in this research contain detailed spatial information about archaeological sites and are therefore not publicly available. Access was granted upon request by the responsible authorities and municipalities for research purposes only.

Bibliography

Basiouka, S. (2024). The Hellenic Archaeological Cadastre: A Land Administration System Specifically Designed for the Documentation and Management of Cultural Heritage. *Land*, 13(7):955.

Bieda, A., Bydłosz, J., Warchoł, A., and Balawejder, M. (2020). Historical Underground Structures as 3D Cadastral Objects. *Remote Sensing*, 12(10):1547.

Buiza, M. and Hekman, S. (2022). Striving for a more positive registration. FIG Congress 2022, Volunteering for the future - Geospatial excellence for a better living Warsaw, Poland, 11–15 September 2022.

Dimopoulou, E. and Gogolou, C. (2013). LADM as a Basis for the Hellenic Archaeological Cadastre. 5th Land Administration Domain Model Workshop, 24-25 September 2013, Kuala Lumpur, Malaysia.

FHA (2011). Flanders Heritage Agency. https://www.onroerenderfgoed.be/ , Accessed: April 2025.

Hevner, A. and Chatterjee, S. (2010). *Design Research in Information Systems: Theory and Practice*, volume 22 of *Integrated Series in Information Systems*. Springer US, Boston, MA, Chapter 2.

Kalogianni, E., Dimopoulou, E., Gruler, H.-C., Stubkjær, E., Morales, J., Lemmen, C., and Van Oosterom, P. (2024). Refining the survey model of the LADM ISO 19152–2: Land registration. *Land Use Policy*, 141:107125.

Kalogianni, E., Dimopoulou, E., Thompson, R. J., Lemmen, C., Ying, S., and Van Oosterom, P. (2020). Development of 3D spatial profiles to support the full lifecycle of 3D objects. *Land Use Policy*, 98:104177.

Kalogianni, E., Dimopoulou, E., and Van Oosterom, P. (2017). A 3D LADM Prototype Implementation in INTERLIS. In Abdul-Rahman, A., editor, *Advances in 3D Geoinformation*, pages 137–157. Springer International Publishing, Cham. Series Title: Lecture Notes in Geoinformation and Cartography.

Kalogianni, E., Janečka, K., Kalantari, M., Dimopoulou, E., Bydłosz, J., Radulović, A., Vučić, N., Sladić, D., Govedarica, M., Lemmen, C., and Van Oosterom, P. (2021). Methodology for the development of LADM country profiles. *Land Use Policy*, 105:105380.

Kara, A., Lemmen, C., Van Oosterom, P., Kalogianni, E., Alattas, A., and Indrajit, A. (2024). Design of the new structure and capabilities of LADM edition II including 3D aspects. *Land Use Policy*, 137:107003.

Koeva, M., Nikoohemat, S., Oude Elberink, S., Morales, J., Lemmen, C., and Zevenbergen, J. (2019). Towards 3D Indoor Cadastre Based on Change Detection from Point Clouds. *Remote Sensing*, 11(17):1972.

Lahaye, M., Dusar, M., Jagt, J. W. M., Kisters, P., Berto, T., Cnudde, V., Dubelaar, C. W., and De Kock, T. (2022). The Transversal Heritage of Maastricht Stone, a Potential Global Heritage Stone Resource from Belgium and the Netherlands. *Geoheritage*, 14(2):49.

Lahaye, M. F. A. and De Kock, T. (2024). Large Scale Mapping of the Historical Underground Limestone Quarries Using Mobile Laser Scanning, a Case Study in Riemst, Belgium. *Geoheritage*, 16(3):78. test.

Lemmen, C., Alattas, A., Indrajit, A., and Kalogianni, E. (2021). FIG e-Working Week 2021. *Saudi Arabia*.

Lemmen, C., Van Oosterom, P., and Bennett, R. (2015). The Land Administration Domain Model. *Land Use Policy*, 49:535–545.

Netherlands (1988). Monumentenwet. Wet van 23 december 1988, tot vervanging van de Monumentenwet, Staatsblad 1997, 291.

Netherlands (2016). Erfgoedwet [Heritage Act], Staatsblad 2016, 275.

Psomadaki, S., Dimopoulou, E., and Van Oosterom, P. (2016). Model driven architecture engineered land administration in conformance with international standards – illustrated with the Hellenic Cadastre. *Open Geospatial Data, Software and Standards*, 1(1):3.

Ramlakhan, R., Kalogianni, E., van Oosterom, P., and Atazadeh, B. (2023). Modelling the legal spaces of 3D underground objects in 3D land administration systems. *Land Use Policy*, 127:106537.

Stoter, J. E. (2004). *3D cadastre*. Number 57 in Publications on Geodesy. NCG, Delft. TU Delft PhD thesis, p. 37.

Theunissen, L. (2024). Een geschiedenis van Archis. Technical Report 291, Rijksdienst voor het Cultureel Erfgoed.

Van Oosterom, P. (2018). *FIG publication - Best practices 3D cadastres*. FIG, extended version edition. OCLC: 1121030695.

Van Oosterom, P., Bennett, R., Koeva, M., and Lemmen, C. (2020). 3D Land Administration for 3D Land Uses. *Land Use Policy*, 98:104665.

Van Oosterom, P., Broekhuizen, M., and Kalogianni, E. (2021). BIM Models as Input for 3D Land Administration Systems for Apartment Registration. Publisher: International Federation of Surveyors (FIG) - Delft University of Technology.

Vlaanderen (2013). Onroerenderfgoeddecreet van 12 juli 2013 [Flemish Immovable Heritage Decree]. Belgisch Staatsblad.

Voûte, R. L., Van Den Hoven, C., Prins, H. S., and Smit, B.-P. (2023). PRACTICAL EXPLORATION OF LOW-COST YET HIGHLY ACCURATE 3D MAPPING TECHNIQUES FOR DOCUMENTATION AND CONSERVATION OF AN EGYPTIAN TOMB (THEBAN TOMB 45). *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, X-1/W1-2023:223–230.

Yan, J., Soon, K. H., Jaw, S. W., and Schrotter, G. (2019). A LADM-based 3D Underground Utility Data Model: A Case Study of Singapore. 8th International FIG workshop on the Land Administration Domain Model 1-3 October 2019, Kuala Lumpur, Malaysia.

Colophon

This document was typeset using LaTeX, using the KOMA-Script class `scrbook`. The main font is Palatino.