MSc thesis in Geomatics

P2 Document

LADM-based 3D system for Archaeological Site Information Registration

Dimitrios Mouzakidis

January 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

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. P.J.M. van Oosterom
	Dipl.-Ing. E.K. (Eftychia) Kalogianni
Company Supervisor:	Ir. R.L. (Robert) Voûte
Co-reader:	XYZ

Abstract

This thesis proposes creating a web-based 3D system for registering and visualizing archaeological sites using the Land Administration Domain Model (LADM). It aims to integrate point cloud data with legal and cadastral information to enhance the management and preservation of archaeological sites. The first section introduces the project's motivation. The second section briefly reviews existing academic work to identify the research gap. The third section presents the research questions, while the fourth discusses the theoretical framework and some methodological steps that will be employed to address the problem at hand.

Acknowledgements

TO BE FILLED OUT LATER

. . .

Contents

List of Figures

Acronyms

1 Introduction

Information and communications technology developments have significantly impacted modern cadastral systems and Land Administration Systems (LASs) in general. Although academia contributes remarkably by researching existing LASs, analyzing good practices in various countries, and creating conceptual models, the responsibility for a comprehensive land administration framework applied to a country's needs is shared among various stakeholders such as government or Land Administration (LA)/geodetic authorities, industry, and academic institutions [Kalogianni et al., 2021]. At the same time, the need to effectively manage land and property rights above, below, and on the ground's surface is growing due to the increasing complexity of both the built environment and the associated rights. 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., 2020a]. Heritage sites, as unique land components, are such 3D objects that demand attention within modern cadastral and LASs to enhance their protection, documentation, and sustainable management. Recent innovations in 3D recording and the display of archaeological entities have focused primarily on the capture and visualization of landscapes, excavations, and objects as point clouds. Thus, the implementation of a 3D Land Administration System (LAS), and more specifically a web-based one, presents challenges, including the need for interoperability among various data formats (e.g.point clouds) and standards, as well as addressing legal, institutional, and technical shortcomings [Kalogianni et al., 2020b]. At the same time, International Standards (ISO) have been used over the last few years, aiming to provide a commonly shared vocabulary for the scientific documentation of Cultural Heritage [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 Cultural Heritage. A standard in modeling Cultural Heritage can be defined as a set of regulations for the correct development and protection of digital data produced by the recordation and documentation of cultural objects. In this context, and based on the Land Administration Domain Model (LADM), the goal of this thesis will be the development of a web-based 3D prototype responsible for the accurate registration and visualization of point cloud data related to archaeological sites along with its legal semantics.

1.1 Research Framework

This section outlines the framework of the research related to 3D cadastral data-base systems and 3D LASs. While closely related, these concepts differ in their focus and scope. A 3D cadastral database system focuses on the technical and spatial representation of land parcels, including their 3D geometries, topological relationships, and storage structures. It emphasizes the precise management of geospatial data and is often implemented to facilitate spatial queries, visualization, and integration of multidimensional data into cadastral models [Oosterom et al., 2018]. On the other hand, a Land Administration System (LAS) encompasses a broader term that includes cadastral systems as one of its components. LAS manages not only the spatial aspects but also the legal, institutional, and social dimensions of land rights, restrictions, and responsibilities [Kalogianni et al., 2020b]. To put it simple, the former will be used in this study for research focusing on the technical implementation of cadastral data, while the latter will refer to studies addressing the conceptual and administrative aspects. Review of relevant scholarly resources, including journal articles, conference proceedings, books, and theses, identifies the fundamental aspects essential for achieving the research goals. Based on the insights gained from the literature, the research was structured around three core pillars: data modeling, data storage, and web visualization (Figure 1.1). These components were identified as critical for developing a robust framework for integrating and visualizing point clouds for archaeological purposes in a LADM-based system.

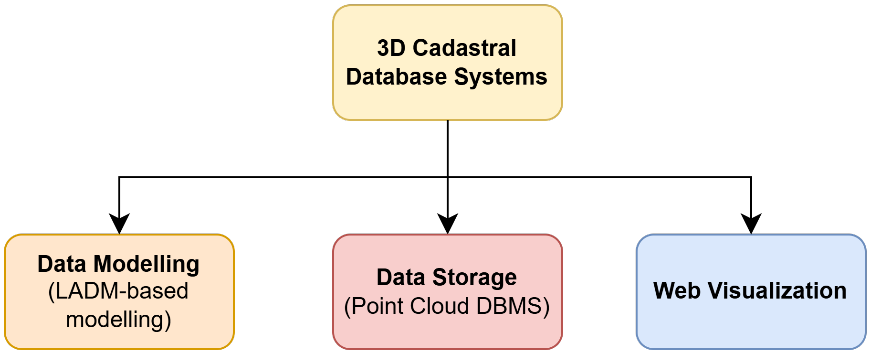


Figure 1.1: Research Framework

2 Related Work

This chapter provides a review of the existing literature and practices related to the topic. By examining key research contributions and identifying gaps in the current body of knowledge, the foundation for the thesis is established.

2.1 Data modeling

This section introduces the legal data model that will be used in the research.

Land Administration Domain Model (LADM) :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 (Rights, Restrictions, Responsibilities (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 stand-alone 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

Part 2 - Land Registration : According to ISO this part of the standard provides an abstract, conceptual model with three packages related to parties (people and organizations), basic administrative units, RRR (ownership rights), 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.

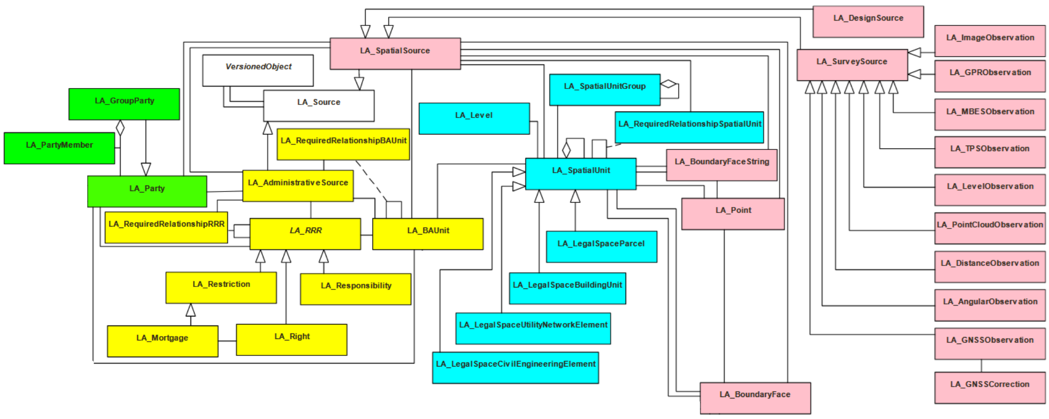


Figure 2.1: LADM Edition II Parts 1, 2

Physical objects & legal spaces: According to LADM, it is important to realize that there is a difference between the 3D physical object itself and the 3D legal space related to this object. The LADM only covers the legal space, which is the space that is relevant for the land administration (bounding envelope of the object). This is usually larger than the physical extent of the object itself (for example including a safety zone). The boundaries of the legal spaces are considered as topological concepts (boundary face and boundary face strings) specifying limits of the legal space and thus limits of the spatial units [Kara et al., 2024]. Figure 2.2, shows mixed use of boundary face strings and boundary faces defining both unbounded and bounded 3D volumes.

On the other hand, 3D physical objects are the physical counterparts of the legal spaces and represent the real-world spatial entities such as buildings, tunnels, archaeological structures, etc. Kara et al. [2024] discuss that legal spaces should be linkable to physical objects either through identifiers or by reusing descriptions of the space. This means that a spatial unit can be described by referring to a building format or by defining its actual shape by geometrical types. In any case, new attributes and default values are used and associated constraints are imposed. Figure 2.3 depicts this relationship in LADM Edition II Part 2.

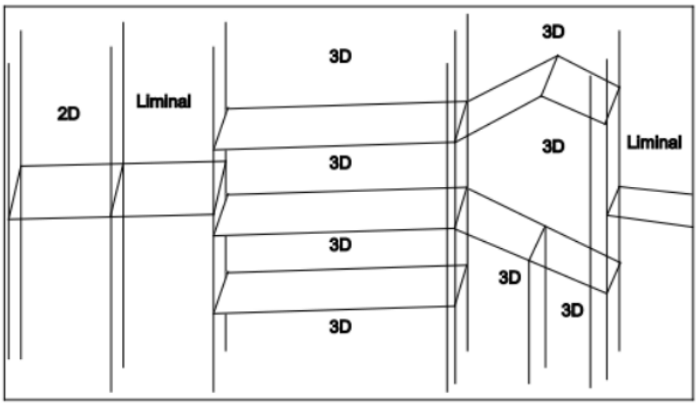


Figure 2.2: Mixed use of boundary face strings and boundary faces

2.2 Data Storage

Point clouds are increasingly utilized in cadastral Database Management Systems (DBMS) as 3D spatial representations due to their ability to capture high-resolution geometric and semantic information about physical environments, making them essential for spatial data modeling.

Importance of point clouds in cadastral DBMSs: According to Janečka et al. [2018], and considering the LADM standard, point cloud data play a critical role in two main situations: first, as a 3D reference, and second, as an input for the creation of 3D parcels. As a 3D reference, point clouds provide precise spatial data that represent the physical environment, enabling the validation and refinement of cadastral boundaries. Additionally, point cloud data serve as a key input for defining 3D cadastral parcels, as they allow for the extraction of volumetric boundaries. For instance, Koeva et al. [2019] demonstrated the use of point clouds for detecting structural changes in indoor environments and deriving precise boundaries for 3D cadastral units. Their approach involved processing point clouds to identify walls, ceilings, and floors, which were then used to create volumetric representations of legal spaces.

Point cloud data type: In object-relational databases point clouds are managed using three primary approaches:

- The first approach involves storing the contents of a LAS file as a Binary Large Object (BLOB) or as a multipoint geometry type within a single tuple, which is efficient for maintaining the integrity of the original file but can limit query performance.
- The second approach stores each point individually, along with its attributes (e.g., x, y, z coordinates and additional metadata), as separate tuples or as objects of point geometry types. This method enables detailed querying and fine-grained spatial analysis but may lead to increased storage requirements and reduced performance for massive datasets.

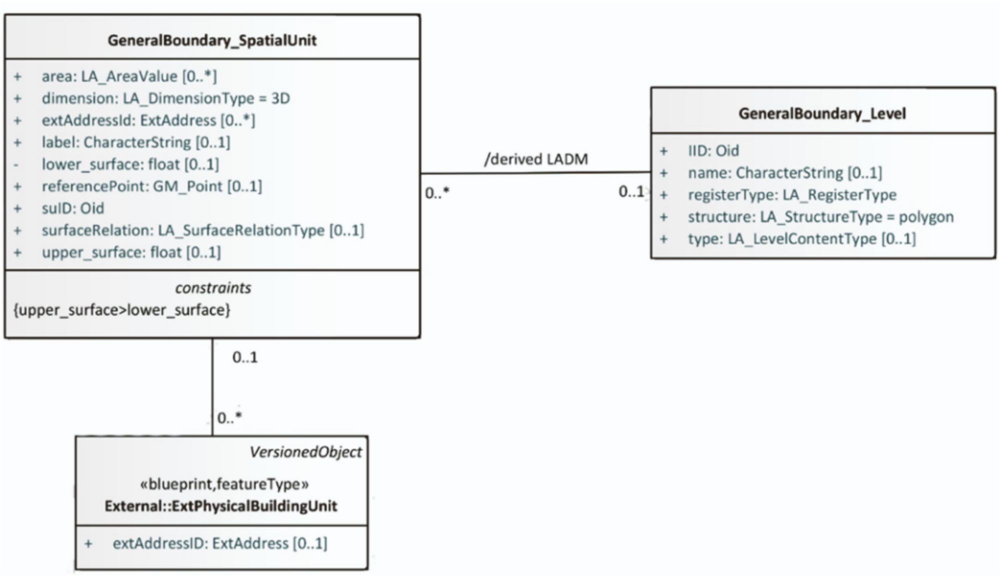


Figure 2.3: Relationship between legal spaces and physical objects in LADM Ed. II Part 2

- The third approach splits the data into coherent blocks, which can be represented as BLOBs, multipoint geometries, or other spatial data types, balancing storage efficiency and querying speed. This approach is particularly advantageous for handling large-scale point cloud datasets, as it optimizes storage while allowing efficient data retrieval and spatial indexing.

These methods reflect the challenges and advancements in managing massive point cloud datasets, as discussed by Van Oosterom et al. [2015]. Both PostgreSQL-PostGIS and Oracle Spatial and Graph have developed their own flexible object types for point cloud data; respectively PC_PATCH and SDO_PC_BLK.

Multidimensional modelling: Designing a database for 3D cadastral systems must take into account the use of multidimensional data to represent both legal and physical boundaries. One major challenge is managing the topological relationships between these boundaries, especially since they may exist in different dimensions. To address this, Ding et al. [2019] proposed a multidimensional topological data structure. Their approach included various spatial and spatio-temporal elements based on the LADM, such as boundary points, lines, faces, 2D and 3D spatial units, and time. They designed a conceptual data model with three main components: cadastral objects, geometry, and topology. Their findings suggest that for multidimensional data, an ideal model should be dimension-independent and able to express topological relationships in a unified way.

2.3 Web Visualization

Opting for a web-based solution is highly practical for dissemination, as web browsers provide a platform that is largely independent of specific hardware or software, allowing it to reach a wide audience with minimal effort required from users. Cemellini et al. [2020] discuss two types of wish lists that need to be taken under consideration. The first one refers to the 3D cadastral data visualization requirements, while the second one to the selection of the 3D web viewer. As Mao et al. [2024] emphasize, urban environments are becoming increasingly complex, necessitating innovative visualization techniques to address challenges like multi-level property rights, overlapping parcels, and underground constructions. The study demonstrates how CesiumJS, a web-based 3D globe viewer, can enable dynamic and interactive 3D visualization of cadastral data, ensuring scalability and user accessibility. One of the prototype's standout features is its ability to visualize Rights, Restrictions, and Responsibilities (RRRs) and associated legal entities through UML instance-level LADM diagrams, directly linking spatial units to the administrative and legal data stored in the backend.

2.4 Relevant studies

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 rights, restrictions, and responsibilities (RRRs) 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. 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 3D (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.

Despite significant advances in 3D Land Administration Systems (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 at the implementation level. 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]. This could raise questions like how point cloud data can be effectively integrated into existing 3D LADM-based models to enhance the management and preservation of archaeological sites. Or, what methodologies can be developed to ensure that these models accurately reflect the spatial complexities inherent in historic areas? By addressing these questions, this research aims to contribute to the body of knowledge by providing a framework for integrating point cloud data into 3D LAS, ultimately facilitating better preservation and management strategies for archaeological heritage. The overall proposal can be illustrated in Figure 2.4.

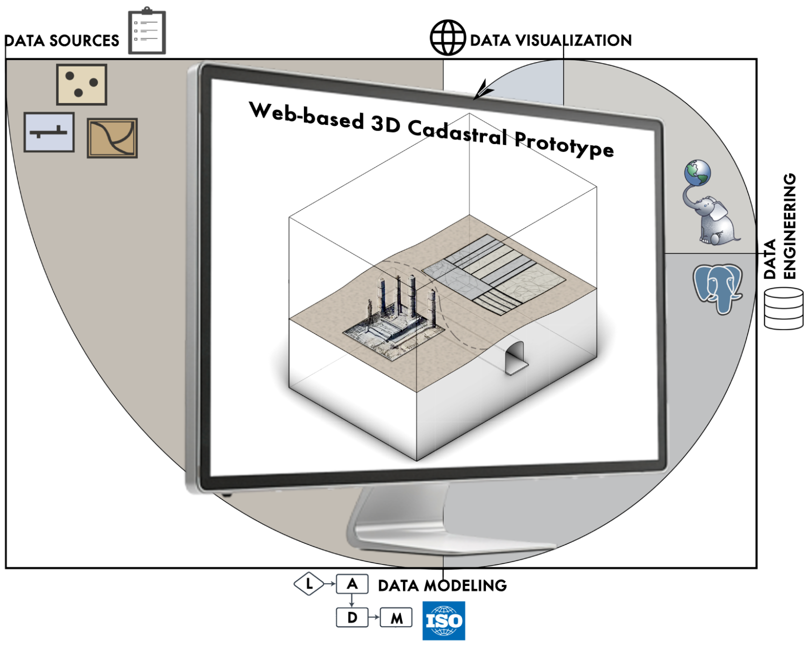


Figure 2.4: Schematic Diagram of overall research proposal

3 Research questions

This chapter outlines the core research questions, sub-questions, and the aim of the proposed work. It defines the specific problem that the research seeks to address. The main research question as well as the sub-questions are listed below:

How can point clouds be processed and integrated as boundary representations into a LADM model to develop a 3D web-based Land Administration System (LAS) prototype for archaeological purposes?

How can point clouds be

- What is the LADM archaeological profile that should be developed?
- How can legal and semantic information be effectively linked to the data format used for 3D boundary representations?
- What is the system architecture for the implementation of a 3D LAS?
- How can the system facilitate interactive visualization and querying of integrated 3D models alongside the database's land administration information?

This thesis aims to integrate point clouds into 3D Land Administration Systems based on the Land Administration Domain Model (LADM) and develop a web-based 3D prototype for visualizing the combination of legal cadastral data and archaeological semantics. By unifying the legal land administration perspective with the rich semantic information of archaeological sites, this research seeks to create a comprehensive 3D system that supports both the preservation of legal property rights and the in-depth study of cultural heritage.

4 Methodology

This chapter describes the methodology to address the research questions introduced in the previous chapter. The general workflow presenting the different steps that will be carried out is depicted in Figure 4.2. Based on the examined case studies (see Chapter 5), both administrative data (e.g., RRR) and geospatial data (e.g., point clouds) pass through a common pre-prossesing step. This indicates their integration in the creation of a UML Use Case diagram (example is depicted in 4.1), which is a visual representation that illustrates the interactions between users (actors) and a system. It captures the functional requirements of a system, showing how different users engage with various use cases, or specific functionalities, within the system. They provide a high-level overview of a system's behavior, making them useful for stakeholders, developers, and analysts to understand how a system is intended to operate from the user's perspective, and how different processes relate to one another. That's an important inital step when one models and exchange geoinformation.

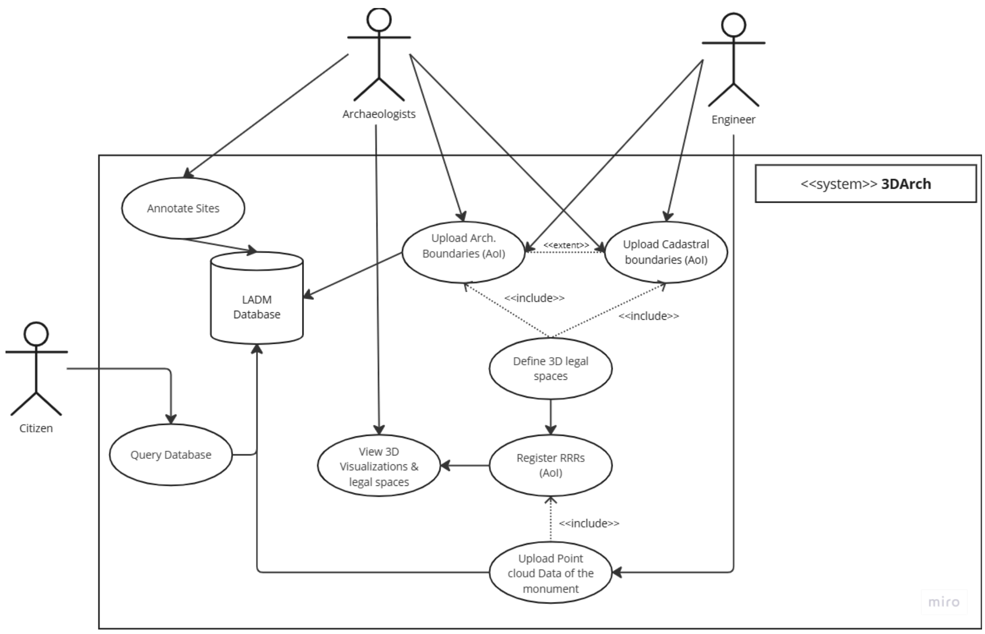


Figure 4.1: Example Use Case Diagram

The rest of the steps include:

- Database Design
- Data Tiling for 3D Visualization
- Server-Side Integration
- Web-Based Visualization

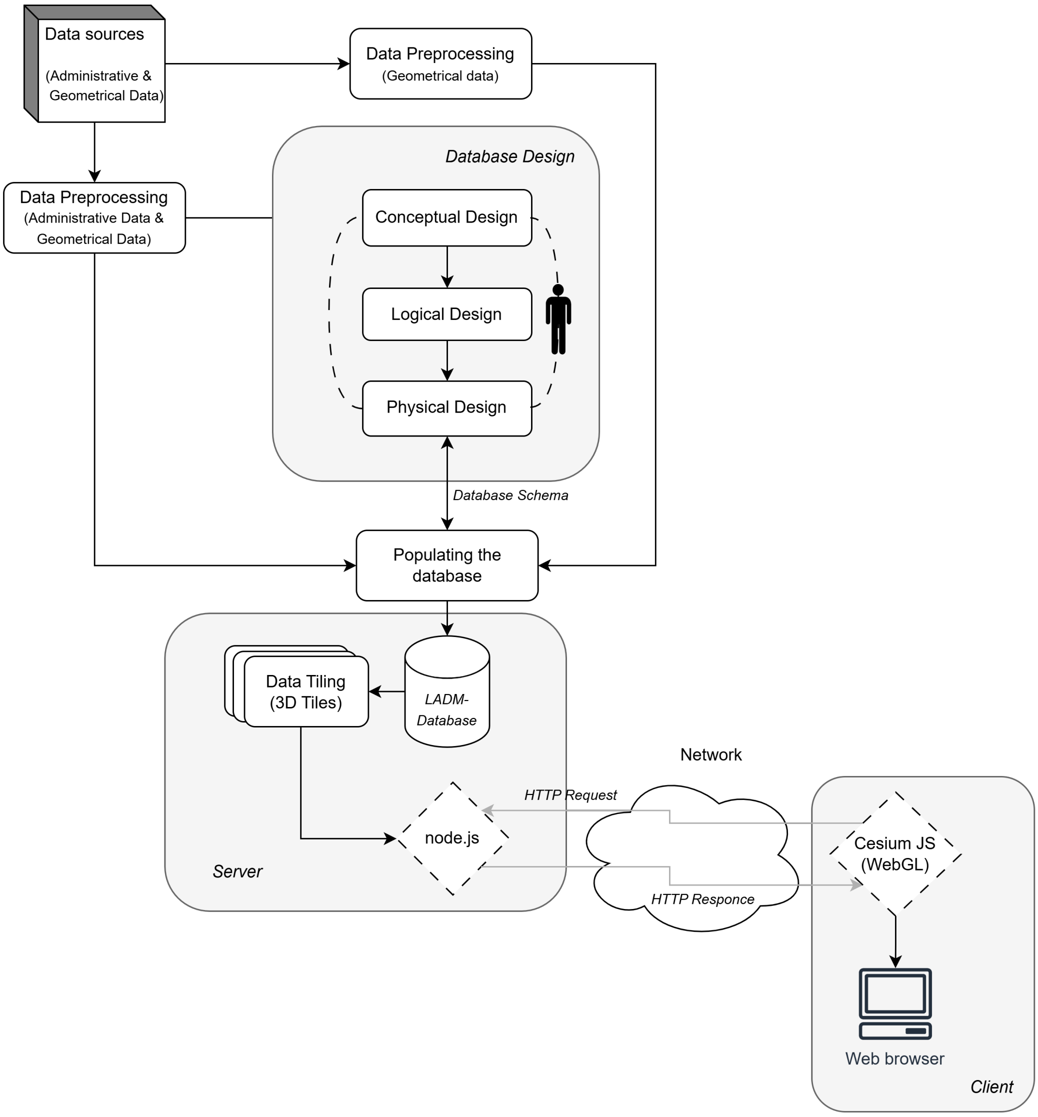


Figure 4.2: Overall workflow diagram

5 Datasets

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

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

After thorough discussions with the thesis supervisors, it was decided that examining archaeological sites in both urban and rural environments would provide a comprehensive evaluation of the model's applicability as different Rights, Restrictions, and Responsibilities are applied to the physical objects in each context. More specifically three(3) case studies (2 in Greece and 1 in Belgium) will be examined and are listed below.

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 (see Figure 5.1b). Figure 5.1 depicts the 2D geometry of the monument, "monument - polygonal", as registered in the **hac!** (**hac!**).

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!**.

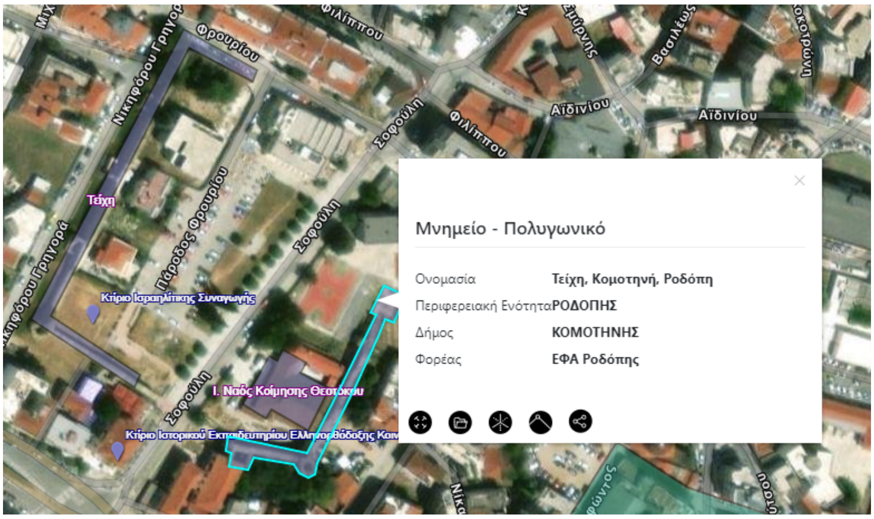
Maastricht Stone: Maastricht Stone is an important heritage stone in the Krijtland at the Belgian-Dutch border. It is omnipresent in local architecture from the Late Middle Ages to the twentieth century, while archaeological remains have evidenced older use [Lahaye et al., 2022]. Until 2019, not all underground quarries had been mapped. A mobile laser scanner was employed to document these underground networks, both to enhance the safety management (to understand the exposure of the built infrastructure and to monitor precursory signs of instability) of this cultural asset and to highlight the diverse characteristics relevant to geo-heritage studies. ([Lahaye and De Kock, 2024]). The documented quarries are located beneath both rural and urban areas and Figure 5.3 depicts a 3D view of point cloud from quarry Grote Berg.

The student has already requested both from the Ephorate of Antiquities of Rhodope in Greece, and the municipality of Riemst in Belgium the following data:

- Point cloud datasets (e.g., generated from laser scanning or photogrammetry in .las/z format, and geo-referenced) representing the sites and the surrounding area (if it exists).

- Topographic map (including cadastral information in .shp format) of the site and its surroundings to contextualize the spatial layout.
- Documentation of legal ownership rights, and other rights, attached to the archaeological site (e.g., government ownership or private land adjacent to heritage sites). CSV/Excel format or Ephorate's recommended format.
- Data outlining preservation rules, legal protections, or restrictions that apply to the site. For example, this could include prohibited construction zones, restricted activities, or maintenance obligations. .Shp format is used for the geometric ones (zones), and CSV/Excel is used for the rest, or Ephorate's recommended format.
- Site-Specific metadata: Historical and cultural metadata about each site (e.g., the site's classification, historical period, artifacts found). CSV/Excel format if the metadata is simple, such as a table with descriptions of datasets, date creation, and coordinate systems used.

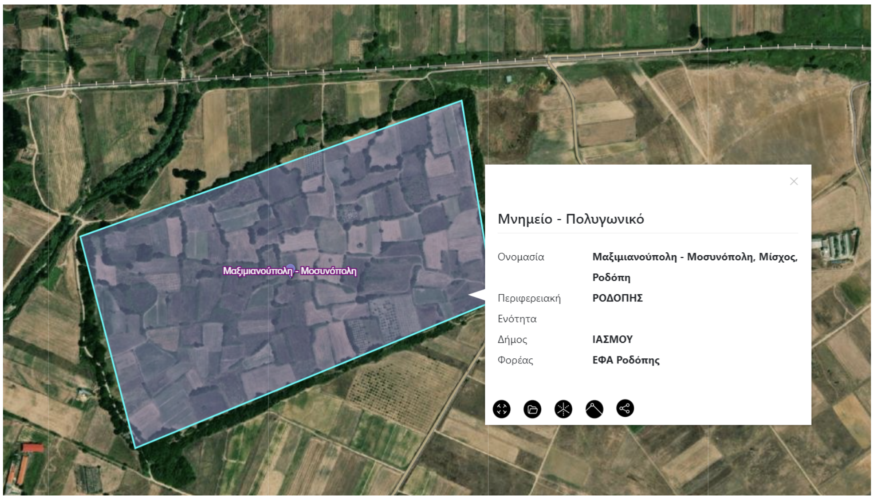
So far, only part of the point cloud dataset representing the Byzantine Wall is available, and depicted in Figure 5.4, while the rest of them will be delivered within the next month.



(a) Monument details in the Hellenic Archaeological Cadastre

(b) Byzantine Wall today

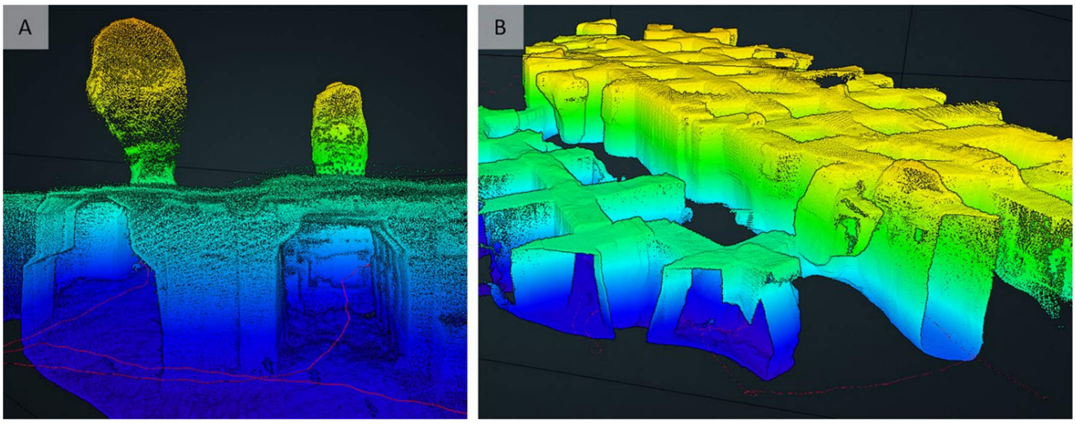
Figure 5.1: Byzantine Wall, Rhodope, Greece



(a) Monument details in the Hellenic Archaeological Cadastre

(b) Remainings of Mosynopolis

Figure 5.2: Mosynopolis, Rhodope, Greece



1.0

Figure 5.3: Point cloud of Maastricht Stone

Figure 5.4: East side of the Byzantine Wall in CloudCompare

6 Softwares and tools

This project is expected to utilize a range of software and tools commonly used for 3D visualization and data management. While the exact tools will be determined during the course of the work, potential options include:

- Enterprise Architect for UML Modelling
- GIS Software: Tools like QGIS for managing, analyzing, and visualizing geospatial datasets.
- Database Management Tools: PostgreSQL with PostGIS will be used for storing and managing spatial, legal, and cultural data, ensuring compliance with LADM standards.
- Point Cloud Processing: CloudCompare for processing and analyzing point cloud data from laser scanning or photogrammetry, PDAL, LASTools
- Web-Based Platforms: CesiumJS, Three.js, and WebGL for creating interactive 3D visualizations and delivering them seamlessly in web browsers. WebGL will serve as the core technology for rendering the visualizations directly within the browser.

7 Planning and Practical Aspects

The following Gantt Chart outlines the main tasks and milestones for the thesis project, scheduled from October 1st to June 30th. While these tasks reflect the general structure and progress of the project, the timeline is subject to adjustments based on feedback, data availability, and evolving requirements. The goal is to ensure a clear and organized workflow that allows flexibility and adaptability as the project progresses.

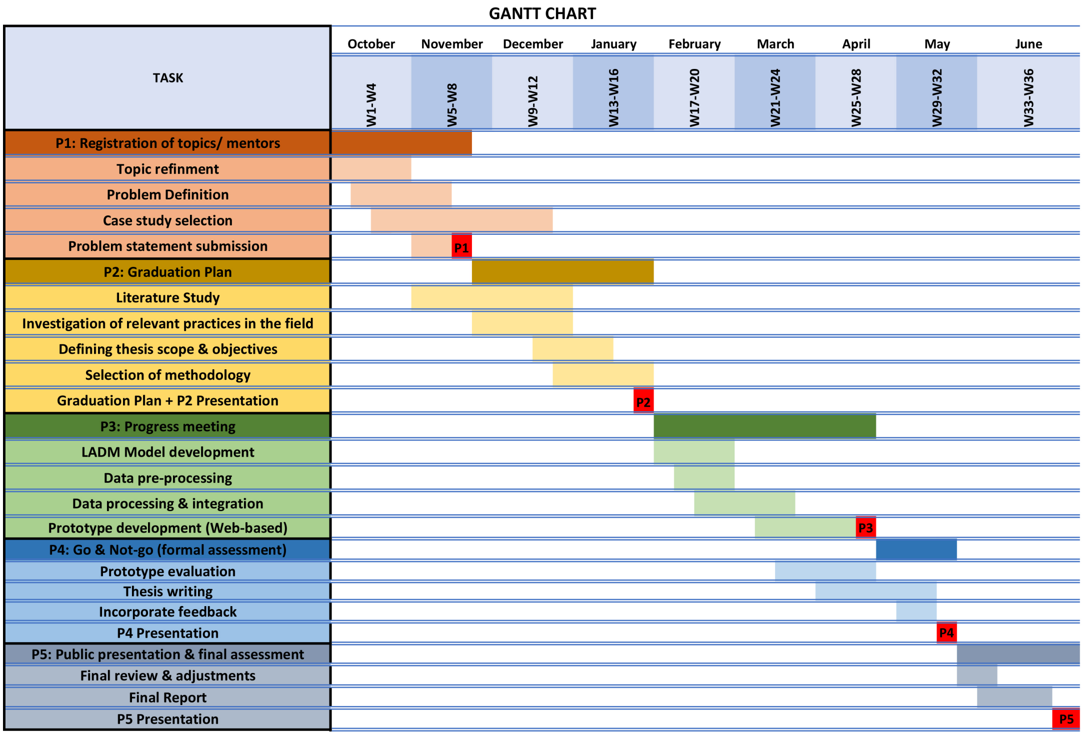


Figure 7.1: Gantt chart

7.1 Supervisors and Collaboration with CGI Nederland B.V

This project benefits from the guidance and expertise of three supervisors. Two supervisors from the university, Prof.dr.ir. P.J.M. van Oosterom (1st) and Dipl.-Ing. E.K. (Eftychia) Kalogianni (2nd), provide academic oversight, ensuring the research aligns with current trends in land administration and Geo-Database Management Systems. Regular meetings every two weeks the supervisors ensure consistent progress, timely feedback, and alignment with the project's goals.

Additionally, Ir. R.L. Robert Voûte (TU Delft Guest researcher & Vice President Consulting Geo-ICT) from CGI NEDERLAND B.V., a leading global consultancy and technology services provider, supervises the project from a technical perspective. CGI offers specialized expertise in 3D modeling, GIS, and database management, playing a critical role in supporting the technical development of the project. Weekly meetings with the company supervisor provide crucial technical guidance and ensure the project leverages CGI's extensive expertise effectively. The company's active involvement in similar case studies, such as the digital documentation of archaeological sites in Egypt, highlights their capability in integrating advanced technologies for archaeological site management.

This collaboration between academia and industry not only ensures the research is rooted in real-world applications but also provides access to cutting-edge tools and methodologies that will enhance the project's outcomes. Additionally, the involvement of external experts, such as archaeologists, enriches the project with specialized knowledge and perspectives that extend beyond the core expertise of professors and industry professionals. These experts bring invaluable field-specific insights and practical experience, ensuring a comprehensive approach to the project and fostering innovative solutions that address both academic and practical challenges.

7.2 Data Usage and Privacy

The requested datasets will be used solely by the student undertaking this research for academic purposes, specifically as part of his MSc graduation thesis. The source data will be securely stored and will not be made publicly accessible for download or subject to unauthorised use. Any visualizations derived from the data (like in Cesium JS) will be strictly limited to those necessary for achieving the research objectives and will only be included following prior consultation with and approval from the Ephorate of Antiquities and municipality of Riemst. The project will fully comply with data privacy and usage regulations, ensuring the proper handling and safeguarding of the provided datasets.

7.3 Benefits to the external stakeholders

This project provides numerous advantages to the external stakeholders introduced above by developing a robust and structured framework for documenting and visualizing archaeological sites. By leveraging a modern, LADM-based system, the project will enhance data interoperability, streamline the management of cultural heritage assets, and support informed decision-making processes. The results of this initiative can serve as a foundation for future digital transformation efforts, contributing to the preservation and promotion of the region's archaeological heritage while ensuring compliance with international standards.

Bibliography

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

Cemellini, B., Van Oosterom, P., Thompson, R., and De Vries, M. (2020). Design, development and usability testing of an LADM compliant 3D Cadastral prototype system. *Land Use Policy*, 98:104418.

Ding, Y., Yang, Y., Wu, C., Shao, H., and Li, H. (2019). A Multidimensional Cadastral Topological Data Model: Design and Implementation. *IEEE Access*, 7:931–943.

Janečka, K., Oosterom, P. V., Kalantari, M., and Ghawana, T. (2018). 3D Cadastres Best Practices, Chapter 4: 3D Spatial DBMS for 3D Cadastres.

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. (2020a). 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.

Kalogianni, E., Van Oosterom, P., Dimopoulou, E., and Lemmen, C. (2020b). 3D Land Administration: A Review and a Future Vision in the Context of the Spatial Development Lifecycle. *ISPRS International Journal of Geo-Information*, 9(2):107.

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.

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.

Mao, P., Oosterom, P. V., and Rafiee, A. (2024). A digital twin based on Land Administration.

Oosterom, P. V., Thompson, R., Janečka, K., Zlatanova, S., and Kalantari, M. (2018). Chapter 3. 3D Cadastral Information Modelling.

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.

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.

Van Oosterom, P., Martinez-Rubi, O., Ivanova, M., Horhammer, M., Geringer, D., Ravada, S., Tijssen, T., Kodde, M., and Gonçalves, R. (2015). Massive point cloud data management: Design, implementation and execution of a point cloud benchmark. *Computers & Graphics*, 49:92–125.

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.

Colophon

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