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Article

Exploiting 2D/3D Geomatics Data for the Management, Promotion, and Valorization of Underground Built Heritage

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Abstract: The scarce knowledge and documentation of Underground Built Heritage (UBH) assets frequently limit their full exploitation and valorization. The aim of this work is to reflect on the techniques, functions, and technical features of a specific case study in a very broad context that can, however, be a building block for the understanding, preservation, and reuse of architectural and engineering values that represent a fundamental trace of the history of a society. Therefore, to fill these knowledge gaps, it was constructed a 3D GIS model, multi-scale, and interoperable database, capable of management, promotion, and valorization of UBH. The case study focuses on the old water supply system of the city of Lisbon, as UBH site, with galleries and cisterns that are points of connection with the urban environment above. For the creation of 3D models of the structure under investigation, it was decided to carry out a survey with Mobile Mapping System as a first step, which allowed the construction of a dense point cloud useful to build 3D models of individual objects. Finally, the 3D models were imported into the 3D GIS environment and multi-information could be linked for each previously identified element for greater knowledge sharing. This research has demonstrated how geomatic techniques can be effectively used in conjunction with the information management systems of GIS to explore this "hidden" heritage and has highlighted the limitations and problems of 3D digitization of the UBH. The results obtained offer the possibility of extending and adapting the methodology to different application contexts and the possibility of customizing the data representation.

Keywords: underground Built Heritage; valorization; mobile mapping; data management; 3D GIS

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1. Introduction

Among the different Cultural Heritage (CH) assets, the category of Underground Built Heritage (UBH), such as subterranean structures built under the surface, is growing in importance.

UBH can be considered part of a broader international heritage management, although national differences affect approaches and methods for its conservation and valorization. The UBH encompasses a set of issues and challenges, raising the need for building a European network to improve the understanding and knowledge and to unlock hidden assets beneath the cities. Modern management protocols and innovative tools are critical issues for an effective valorization of UBH. There are two main issues: (a) a lack of experts with a broad vision of the different possibilities for enhancing the landscape; (b) the need to reconnect the places overcoming the marginalization from which it suffers today. The scarce knowledge and documentation of UBH often limits their full exploitation: too often, the planning process do not consider the "underground" due to its "invisibility". Geotechnical and geo-environmental concerns, together with the presence of archaeological sites and infrastructures, give the perception that underground space is an expensive and high-risk area of intervention [1,2].

With the advancements of digital and mobile technologies, these issues of knowledge deficit can be overcome. Regardless of the type of object to be preserved (archaeological sites, underground heritage, historic buildings), the process of digitization and data collection can be applied to any cultural asset; what makes data accessible, and durable is the process of organization and management in a simple and reliable way.

The conservation and enhancement of CH, including the UBH, cannot be reached without the combination of data from different disciplines, each one with specific methods, information resources, and software [3]. Therefore, the concept of interoperability between information management systems is fundamental to ensure an integral and complete flow of information. However, this concern still remains unresolved [4–6]. Indeed, one of the trending topics in Information and Communication Technologies (ICT) research for CH is the topic of data integration, for which many researchers have been working on the combination of 2D/3D data and GIS data for several years [7].

This is precisely one of the reasons that should make one aware of the need to develop and promote digital and innovative technologies. The potential offered by technologies such as MMS (Mobile Mapping System) or GIS (Geographic Information System) in the field of geomatics, for the acquisition of digital data and design and management of information, is considered an important task for the valorization of CH.

The aim of this paper is to reflect on the results that the integration of 3D data and GIS can provide for enhancing the knowledge of heritage assets. It addresses techniques, functions, and technical features used to collect data and create a visualization for a heritage asset that is underground and thus hidden for the most people. It takes this specific case study to discuss how it can be a building block for increasing the understanding of an asset, thus, paving the way for its preservation and reuse. As a case study, the aqueduct Águas Livres system is used due to its architectural and engineering values that represent a fundamental trace of the history of Lisbon. The objective is to develop an information platform, a multiscale and interoperable database, useful for the development of conservation strategies and for increasing the attractiveness of the UBH setting.

Our experiment has been conducted within the framework of the COST Action Underground4Value [8]: a European network aiming to promote the UBH as a valuable resource to be celebrated and preserved and, when sustainable, to be reused and valorized, achieving its full potential to support local community development [2].

The empirical research took place in the city of Lisbon, where a complex network of above-underground asset, concerning the drinking water system, is nested within the urban environment, making the validation compelling and generalizable. The old water supply system of the city of Lisbon, Aqueduto das Águas Livres, represents a case with enormous potential to be exploited, with several elements of historical and geographical continuity connecting different areas of the city. Citizens and tourists alike are avid in relation to underground heritage, considering the strong demand for visits to the Roman galleries of Baixa Lisbon [9]. Many elements have already disappeared from the city, but they still exist in photographs, engravings, cartographies, and descriptions by authors of the past [10].

The proposed methodological approach is based on the need to create a single knowledge model according to a strategy that integrates the latest technological developments in terms of surveying and 3D representation, allowing to merge and visualize multiple layers of information about the objects of study, whose peculiarity is precisely their "invisibility" and complexity due to their underground nature.

We can thus summarize the main contributions of this manuscript as follows: (i) providing an information system prototype capable of managing heterogeneous data for the management of UBH, (ii) optimizing the 3D representation of above/underground heritage with different LODs, and (iii) applying the methodology in an urban scale benchmark setting for its validation.

2. State-of-the-Art

2.1. Underground Built Heritage Planning Approaches

Despite its importance, studies on the management, valorization, and planning of UBH are very limited. This is the context for the COST Action Underground4Value [8]; to gain knowledge on UBH, Underground4Value makes use of different methodological frameworks, such as sharing knowledge on different aspects of UBH, analyzing paradigmatic case studies, and thus building a classification of the underground heritage based on type, function, and potential. Crucially importance is the development of strategies for its reuse and valorization, including new approaches to embrace such assets into spatial planning and to raise community awareness of UBH [8,11]. One central concern of the Underground4Value is attached to not-well-known heritage assets and their adaptative reuse [12].

Typologies of UBH sites are varied and could include natural and anthropic caves, underground burial/rites structures, mines and quarries, other man-made caves for exploitation and dwelling, underground infrastructures (cisterns, ancient drainage systems, tunnels, etc.), ancient, buried structures and settlements [11]. The term "underground" can take on different meanings; in this specific context, it can refer to heritage, geology, and spatial planning. The Underground4Value planning approaches adopt a comparative case study methodology with an evaluation process to gain information and lay the groundwork for a theoretical framework. The cases differ in terms of reuse maturity, communication strategy, and international stakeholder involvement. The analysis of different cases enables to distill lessons towards transferability of knowledge and experience considering cultural and national regulatory differences.

The functional, social, and cultural approaches define the process of activating and promoting a UBH, exploiting the transition from an undervalued asset to one that provides a positive effect by harnessing the power of the community and working with the community. Activating and promoting UBH is an extremely challenging undertaking. As a transition process, it requires a conceptual logic that promotes innovative and integrative capacities. This logic is based on two main premises: the active involvement of all stakeholders involved and/or interested in UBH (central government and local authorities, scientific and technical personnel, economic agents, and the public as organizations, groups, or individuals), and the impact of participatory planning and processes on the success of UBH projects [12].

Regarding the advancing knowledge, documentation and visualization, several technologies were discussed, including technologies for non-invasive UBH diagnosis, innovative ICT tools for monitoring, portable 3D mapping systems, crack and water leakage sensors, tools for simulating changes in material characteristics due to climatic effects, evaluation protocols for possible uses of UBH sites, imaging in different spectral ranges, and virtual platform for enhancement and preventive conservation.

2.2. Geomatic Tools for UBH Management and Knowledge

The association between geomatic techniques and ICT in the field of cultural heritage, thanks to the generation of multimedia products, fosters new methods of management and knowledge of CH assets.

Over the last years, technological development has made it possible to have more and more innovative and efficient tools for the acquisition of accurate and precise data and for their effective processing in terms of automation, speed, and data quality [13]. Geomatic sensors presents numerous application possibilities that depend mainly on the degree of differentiation of the available methodologies according to the needs and expected results of their use: level of detail, level of accuracy, timing, morphology of the object, position of the object to be surveyed, etc.

Three-dimensional (3D) surveying of underground environments, from the point of view of the criticalities that can affect the acquisition of metric data, depends on the intrinsic characteristics of the site, i.e., it is conditioned by complex environmental and construction factors such as poor lighting, narrow and variable-height passages, as well as articulated paths. For these reasons, working in underground environments requires the development of methodologies that address the problem through multiple approaches. The use of mobile geomatics devices such as Mobile Mapping Systems (MMS) lends itself very effectively to surveying an architectural heritage such as the underground environment, due to its morphological characteristics and the objective difficulties of surveying [14–16].

Thanks to digitization and digital archiving, historical and bibliographical documents related to cultural heritage can be converted into digital formats to ensure sharing, easy access, and the possibility to exploit them to create new forms of documentation and analysis. The integration of digital data, from historical and biographical research, and 3D models, from geomatic surveys, in the field of CH, has become inseparable in recent years, not only in advancing knowledge, for diagnosis, and documentation purposes, but also in valorization, use and management of CH objects [17–19].

The GIS environment, by combining various types of data, becomes a functional tool for documenting and promoting CH asset, as well as for research and dissemination purposes. The concept of HGIS (Historical GIS), referred to CH, has been introduced in the literature as "interdisciplinary approach that integrate the most advanced methods and tools of the geographic information sciences with the sources and questions of geo-historical and historical research, in order to emphasize the importance of contexts and spatial relationships for understanding historical dynamics" [20]. HGIS becomes a complementary tool for documentation and preservation of historical artefacts [21,22], to which geomatics can provide support for various purposes.

Using existing historical cartography, in order to obtain spatial and architectural reconstruction of the objects characterizing the urban area with underground structures under exam, a georeferencing operation is required. By importing this historical map into GIS, it is possible to geo-localize and overlap to the current cartography. Georeferenced maps are still digital images but are useful to extract information concerning an urban area. Building footprints, which can be derived from these 2D maps, are useful for obtaining a 3D reconstruction of an urban area. This 3D model, processed with graphics tools, can then be imported into the GIS, facilitating a visualization development from 2D to 3D [23,24].

The 3D GIS city models, based on the geometric complexity, dimensionality, and attributes of the 3D modeled object [25] are characterized by a multi-scale representation referred to the level of detail (LOD) concept of the OGC standard [26]. LOD 0 and 1 models can be generated from the available cartography, while for higher levels of detail, more information must be obtained to help define the volumes and architectural and structural details of the buildings that compose the urban environment. For this second aspect, the data obtained from geomatic surveys, as point clouds, can represent a form of enrichment of the volumetric and spatial definition of the individual building [27,28] and for underground environment.

There are no similar case studies in the literature where they integrate through 3D GIS examples of UBH connected to the urban environment above. Researchers used 3D GIS for the analysis of a single underground historical artefact. GIS is exploited because of its functionality to better manage information in the form of thematic maps, 3D models, and attribute tables, containing various types of data, connected to it [29]. Regarding the 3D modeling of underground context spaces, if the survey is carried out with static geomatic sensors such as 3D TLS, the final model will present a high level of accuracy thanks to the high resolution index given by the instrument [30,31]. In the case of surveying a long underground environment, the mobile mapping solution guarantees speed and completeness in surveying although it does not provide the same level of accuracy as static sensors due to the low value of resolution [32–34].

In conclusion of this state-of-the-art analysis, the integration of geomatic tools such as information technology, cartography, topography, photogrammetry, laser scanning, and GIS, fosters a multidisciplinary approach for the management, promotion, and valorization of cultural assets, as in the case of UBH.

3. Materials and Methods

For the implementation of a multiscale 2D/3D GIS, the research was carried out following the workflow depicted in Figure 1. Considering the above-mentioned objectives, first a historical, cultural, and architectural analysis was carried out. Thus, we collected bibliographical, photographic, and cartographic information about the selected case study and its relationship with the evolution of the city and its infrastructures. Data collection also includes 3D surveying performed with the discovery of the extensive and valuable heritage on site. All this data is then processed, a relational database is created to collect non-geometric data, and processing of survey data is conducted. The next phase concerning data management in 2D GIS is as follows. Features are identified on map and their attributes are collected in a linked table. To test the data integration, a methodology was adopted that considers the modeling phase for a virtual 3D reconstruction of the underground and urban environments according to the concept of LOD. The 3D GIS ensures to gather all data fostering the integration of 2D data, 3D models, and point clouds. Using an open-source viewer platform, the data sharing is guaranteed.

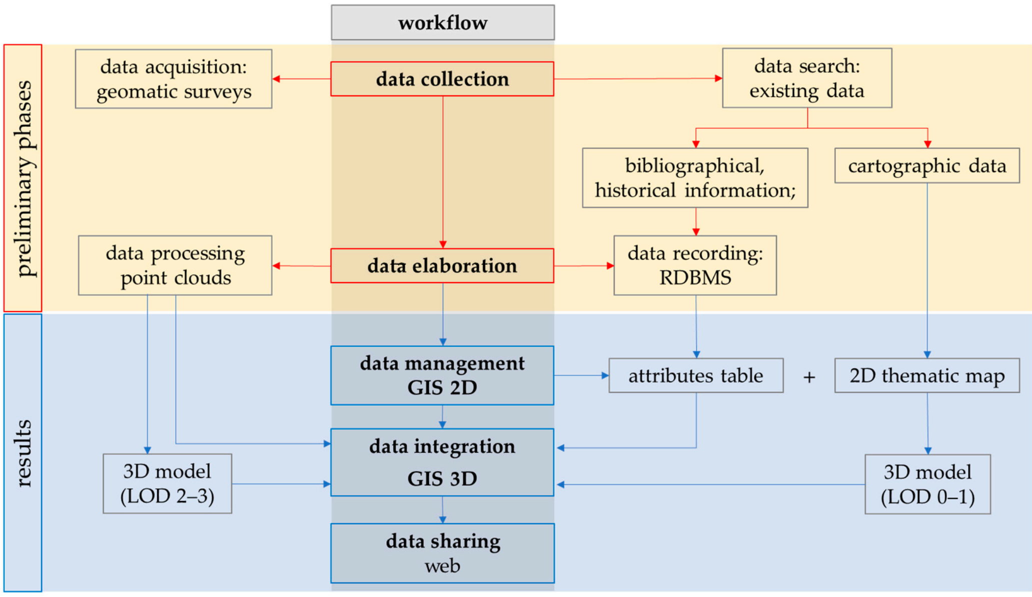


Figure 1. Methodological workflow.

3.1. Case Study: Lisbon Underground, Heritage to Be Valorized

Lisbon, which lies at the mouth of Tagus River into Atlantic Ocean to the west, has paradoxically always suffered from water shortages. The Aqueduct Águas Livres was built in the 18th century with the aim of supplying drinking water to the city. It is a remarkable work of hydraulic engineering and architecture, classified as a national monument. However, over the years, with the advent of new infrastructure, it has lost its purpose, despite its vernacular, industrial, and historical heritage. The water, once in Lisbon, was channeled through a network of canals, mostly underground, about 12 km long (Figure 2).

Considering the extent of the water system, this study focused on the Principe Real area, in particular, on the Galeria do Loreto and the two reservoirs, the Reservatório da Patriarcal and the Reservatório da Mãe d'Água das Amoreiras, which, together with the different access points to the underground environment, represent points of connection with the urban environment above (Figure 3). The Galeria do Loreto comes from the Reservatório da Mãe d'Água. It has a total length of 2835 m, including its branches. At present, it is the only gallery that can be visited, with a 1.5 km underground section that ends at the Reservatório da Patriarcal, in the Jardim do Príncipe Real [35,36].

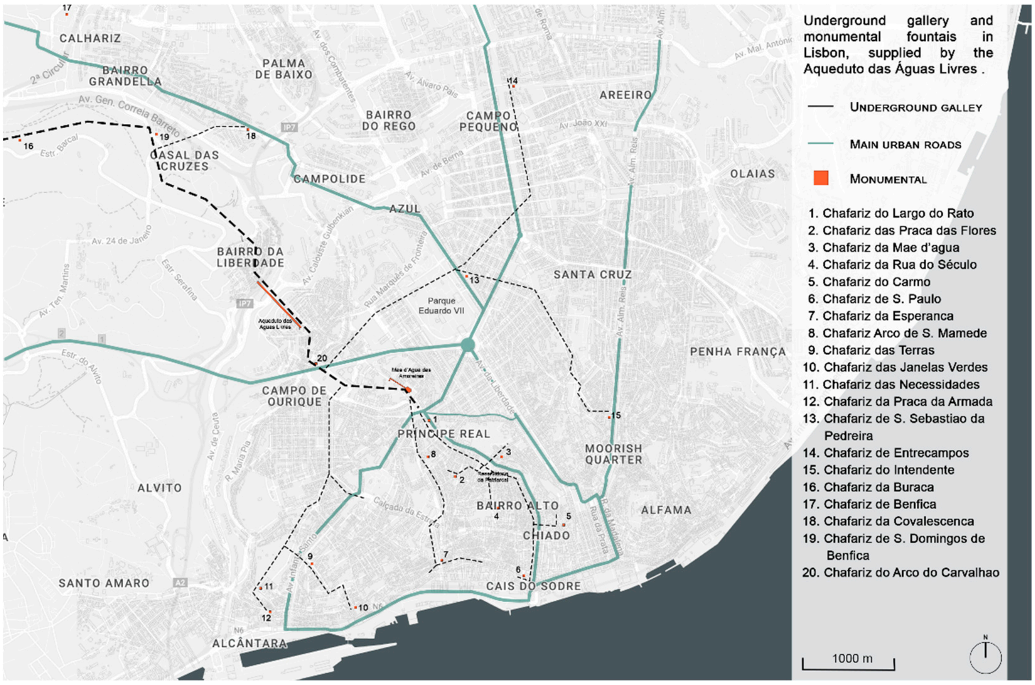


Figure 2. Map of the underground galleries belonging to the Lisbon aqueduct (© L. Gorgoglione).

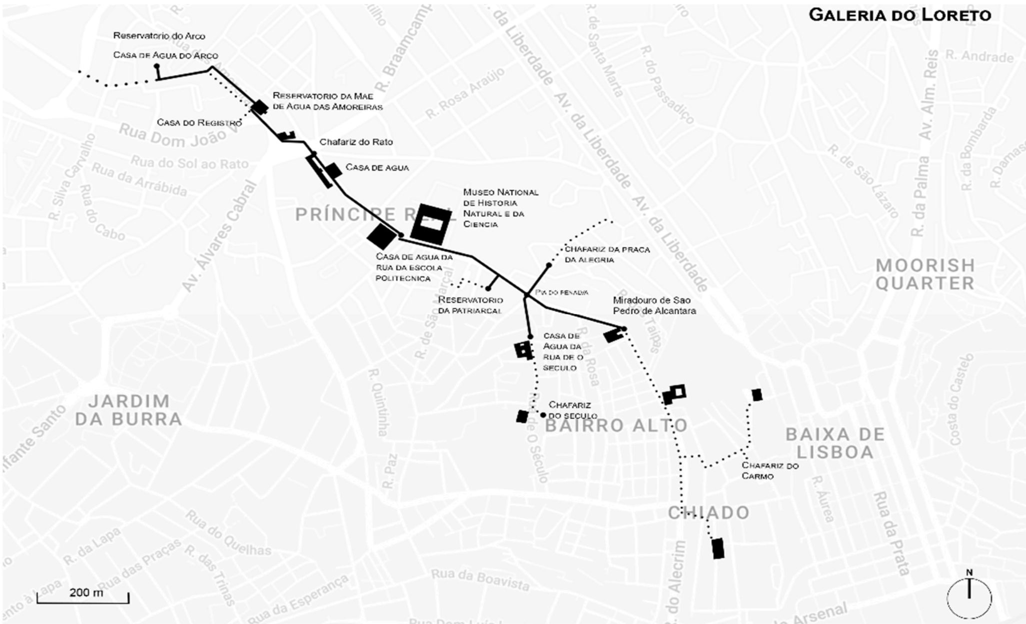


Figure 3. Galeria do Loreto, Lisbon (© L. Gorgoglione).

The underground galleries, cisterns, fountains, and gardens remain a hidden heritage. Instead, they must be visible and exposed to the public in an intelligent and interpretive manner, as an attractive and dynamic factor in the underground. There has been a very significant effort to recover this heritage by the Empresa Portuguesa das Águas Livres (EPAL) [37], the public enterprise for water supply. The opening of the underground galleries to the public is an example of this. It must be remembered that the visits must take place safely, which requires significant investment and the resolution of various constraints in the specific case of each gallery. There is great potential that requires a high level of planning. Although EPAL assumes greater institutional and financial responsibility, an ambitious project to rehabilitate the Águas Livres tunnels can only be realized with broad institutional involvement. It is not only a matter of physical recovery and heritage conservation, but also of its smart valorization. The Museu da Água [38], which is part of a global network of Water Museums promoted by UNESCO, was created because of all these considerations and has two main objectives: firstly, the valorization of a historical asset by making it usable again as a public space and secondly, raising awareness of environmental issues of primary importance through a multimedia exhibition route. External communication is one of the museum's greatest weaknesses, unlike the company which does not need to advertise its precious liquid because it has a monopoly on the market in the sale of water [10]. All cores must be made public and have a lively dynamic. Communicating is also a way of safeguarding and transmitting CH. Digitization and new technologies can play a fundamental role in a major restoration and dynamization project of the Águas Livres galleries [10]. Is it possible to structure paths and trails to see inside the structures that cannot be entered (tanks, degraded sections), and to discover fountains that no longer exist (e.g., using photographs for Augmented Reality). The possibilities are limitless when appropriately combined with the heritage and the urban dimension. However, without surveys and monitoring tools, which are missing or considered too costly, underground sites, once they have lost their original function, often remain forgotten landscapes, abandoned and in a poor state of conservation [10]. Comprehensive mapping of this hidden heritage is the first step in filling knowledge gaps, providing a reliable and adequate representation of built spaces and their geometry.

For these reasons, this study aims at providing support for the Museu da Água as a step for the development of methodologies that address the problem through multiple approaches. We have chosen to use the tools and methodologies of geomatics. In this case, is very effectively suited to the survey of an architectural heritage such as the underground, due to its morphological characteristics and the objective difficulties of surveying.

3.2. Collection of Existing Data

Concerning the availability of sources, the data were partly acquired using datasets available in the GIS Lisboa platform of the Câmara Municipal Lisboa (City Council) and partly from the analysis of historical raster cartography (Figure 4). In detail, datasets were downloaded from the GIS Lisboa concerning the Architecture of Water and the National Museums, from which a selection was then made only for the parts to be used for the purposes of the study [39]. Through the Centre for Historical and Technical Documentation (CDHT) of EPAL [40], it was possible to access online some digitized plans of Lisbon from the second half of the 19th century, including plans of the water distribution network in the city, the underground gallery, and the two reservoirs.

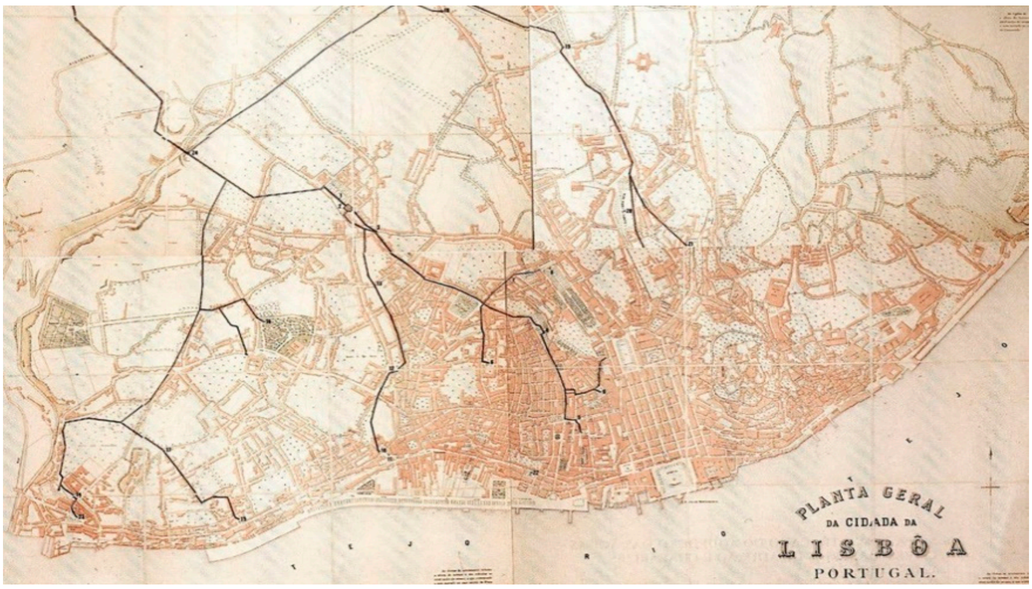


Figure 4. Historical cartography of Lisbon aqueduct, dating from 1990 (© CDHT—X-arqWeb).

3.3. Surveying Techniques: Data Acquisition and Processing

The geomatic survey phase was the most important part, in terms of timing and organization, as the available documentation proved to be very meagre. After considering the architectural characteristics of the site, the survey campaign was conducted based on an already complete knowledge of the formal and dimensional characteristics of the area. This facilitated the choice of instrumentation to be used and allowed the acquisition of data in two distinct phases: one for the acquisitions of the surface parts and external spaces and the other for the underground spaces.

The acquisition of 3D data was carried out for a part of Galeria do Loreto (approximately 900 m long) and for the two reservoirs, Reservatório da Patriarcal and da Mãe d'Água das Amoreiras. Acquisitions were also made for the external spaces and the connections between them.

For the data collection, we chose to adopt the Mobile Mapping Systems (MMS) based on SLAM technology, which allows to map a 3D space by keeping track of the relative position of the device within the area to be surveyed. These systems can also be used in the absence of Global Position System (GPS) coverage, making them a viable choice for underground contexts. Furthermore, the use of MMS can be considered a viable alternative for mapping underground structures, allowing the collection of huge amounts of data, reducing acquisition times and with sufficient accuracy, without the need to use ground control points. The data processing and the mapping in local reference system is done automatically by the device as the operator travels along the route, thanks to the SLAM algorithm, in both closed loop path and linear short paths [41].

The acquisitions were performed at ground level in hand-held mode and the LiDAR instrument, the Kaarta Stencil 2–16 (Figure 5a) (Table 1) [42], supported on a telescopic pole by an operator, was used in outdoor, indoor, and underground environments and in both wide and narrow spaces (Figure 5b).

The various environments were previously inspected in order to set the parameters of MMS according to the types of environments to be detected (Table 2) [42] and to identify any critical issues that might affect the final result. Poor lighting (in indoor and underground environments) for the visual-based feature tracker, the presence of people and moving vehicles (in outdoor environment) and the presence of smooth or reflective surfaces, such as the tunnel walls and the water basin inside the Reservatório da Mãe d'Água das Amoreiras (in indoor environment) might cause a loss of orientation or increase noise effects in the recording of the point clouds.

(a) (b) (c)

Figure 5. (**a**) The MMS Kaarta Stencil 2–16; (**b**) An operator using the MMS detecting the urban environment; (**c**) Top view of the 3D point cloud and closed loop trajectories (red lines) made with the MMS.

Table 1. Technical specifications of the MMS Kaarta Stencil 2–16.

LiDAR	Laser unit Acquisition mode Range FOV Accuracy Speed	Velodyne VPL-16 Time of Flight 1 m [min]–100 m [max] 360° × 30° ±30 mm 300.000 points/sec
Features Tracker	Image resolution Frame rate Image colors	640 × 360 50 Hz black&white
IMU	Type DoF (degree of freedom)	MEMS X,Y,Z, roll, pitch, yaw
Computer	Processor OS Storage Output (data format)	Intel NUC 7i7 Quad Core Ubuntu Linux 1 TB .ply, .las
Physical characteristics	Dimension Weight	162 mm × 111 mm × 141 mm 1.73 kg

Table 2. Parameters setting for the mapping system (Kaarta Stencil 2–16).

Typical Parameters to Set		**Types of Environments**	
		Structured Outdoor–Large Indoor	**Tight Indoor-Underground**
Scan registration	Voxel size [m] Blind radius [m]	0.2 2.0	0.1 1.0
Laser mapping	Corner voxel size [m] Surface voxel size [m] Surrounding voxel size [m]	0.2 0.4 0.6	0.1 0.2 0.3

Therefore, different types of settings were performed according to the environment considered: external urban space, i.e., the road connecting the Reservatório da Mãe d'Água das Amoreiras to the Reservatório da Patriarcal; outdoor and indoor spaces of historical buildings, represented by the Reservatorio da Mãe d'Água das Amoreiras and the Reservatório da Patriarcal; underground building heritage, represented by the Galeria do Loreto. In the first two cases, routes were carried out according to closed loops at the same location as the starting point and intersecting roundtrips, during the mapping operation. Through the tracking camera, integrated into the device, the trajectory made during the acquisition was calculated and recorded. The saved trajectory is useful, in the post-processing phase, to make corrections in case of distortion or drift may affect the point clouds. This operation is possible thanks to the application of "Loop Closure" function inside Kaarta Stencil 2–16 computer which re-computes the point cloud after the correction made on the trajectory line (Figure 5c). This way, the system can verify that the drift error is removed. This operation was done for all the sub-set of point clouds done for the whole surveyed area. After that, common points among the different scans were identified in combination with the Iterative Closest Point (ICP) algorithm, in order to merge them within the same reference system, finally considering the survey as a whole.

There are numerous changes of direction in the underground environment, and the path runs on a single plane at depth, except for the connecting stairs to the entrances/exits. The interior surfaces of the tunnel are made of sandstone, and due to the high humidity in this place, there is water on the surfaces. The underground complex is artificially illuminated by small lamps installed along the path, so that the light intensity is subdued, creating shaded spaces. Other critical issues encountered are the width (of max. 1.50 m) and the variable height (of max. 2.30 m) of the tunnel, which posed a problem in terms of data acquisition due to the limited range of the instrument, which compromised the data processing phase. However, considering the very short acquisition times, compared to other mapping systems, the result is acceptable (Table 3).

Table 3. Data acquisition parameters.

N. Scan	ID Scan	Scan Time (h:m:s)	Trajectory Length [m]	Type of Environment
1	Reservatório da Patriarcal_	00:04:19	356.60	outdoor
2	Reservatório da Patriarcal_ Street 1	00:03:46	350.30	outdoor
3	Reservatório da Patriarcal_Street 2	00:02:36	223.20	outdoor
4	Reservatório da Patriarcal_Street 3	00:07:16	666.30	outdoor
5	Reservatório da Mãe d'Água _Ext 1	00:05:38	426.40	outdoor
6	Reservatório da Mãe d'Água _Ext 2	00:05:50	516.80	outdoor
7	Reservatório da Mãe d'Água _Ext 3.1	00:03:23	236.00	outdoor
8	Reservatório da Mãe d'Água _Ext 3.2	00:02:49	236.90	outdoor
9	Reservatório da Mãe d'Água _Indoor 1.1	00:04:02	268.10	indoor
10	Reservatório da Mãe d'Água _Indoor 1.2	00:01:49	122.30	indoor
11	Reservatório da Mãe d'Água _Roof	00:03:20	270.30	outdoor
12	Reservatório da Mãe d'Água _BeforeTunnel	00:00:40	31.60	indoor/outdoor
13	ConnectionIndoor_Roof	00:01:56	66.10	indoor
14	Galeria do Loreto_FirstPath	00:01:28	119.50	underground
15	Galeria do Loreto_FirstStop	00:00:36	21.80	underground
16	Galeria do Loreto_SecondPath	00:03:36	270.90	underground
17	Galeria do Loreto_SecondStop	00:00:51	22.20	underground
18	Galeria do Loreto_ThirdPath	00:03:22	317.60	underground
19	Galeria do Loreto_FourthPath	00:00:59	55.00	underground
20	Galeria do Loreto_TowardTunnel	00:00:47	36.00	underground
	Total	**1 h**	**4.6 km**	

Once all the scans were merged in the same reference system and aligned (Figure 6), in order to exploit the potential of GIS-BIM integration, the georeferencing was essential. However, given the lack of Ground Control Points, we identified known points from the cartography, and used them to only perform a roto-translation. Depending on the chosen scale of representation coming from the cartography, the allowable error was determined according to the existing literature in the field of CityGML [43].

For the scan alignments, a range of error of 0.05 m to 0.20 m was found (Table 4). This range of errors is considered tolerable for the type of representation and use of the data. For the purposes of this study, a higher level of detail was not required.

Table 4. Accuracy of point clouds alignment.

Scan 1	Scan 2	n. Equivalent Points	RMS [m]
Reservatório da Mãe d'Água _Ext 1	Reservatório da Mãe d'Água _Ext 2	3	0.068488
Reservatório da Mãe d'Água _Ext 2	Reservatório da Mãe d'Água _Ext 3.1	3	0.073644
Reservatório da Mãe d'Água _Ext 2	Reservatório da Mãe d'Água _Ext 3.2	3	0.146506
Reservatório da Patriarcal_Street 1	Reservatório da Patriarcal_Street 2	3	0.083757
Reservatório da Patriarcal_Street 1	Reservatório da Patriarcal _Street 3	3	0.067467
Reservatório da Mãe d'Água _Ext 2	Reservatório da Mãe d'Água _Roof	3	0.180208
Final Alignment			**0.162591**

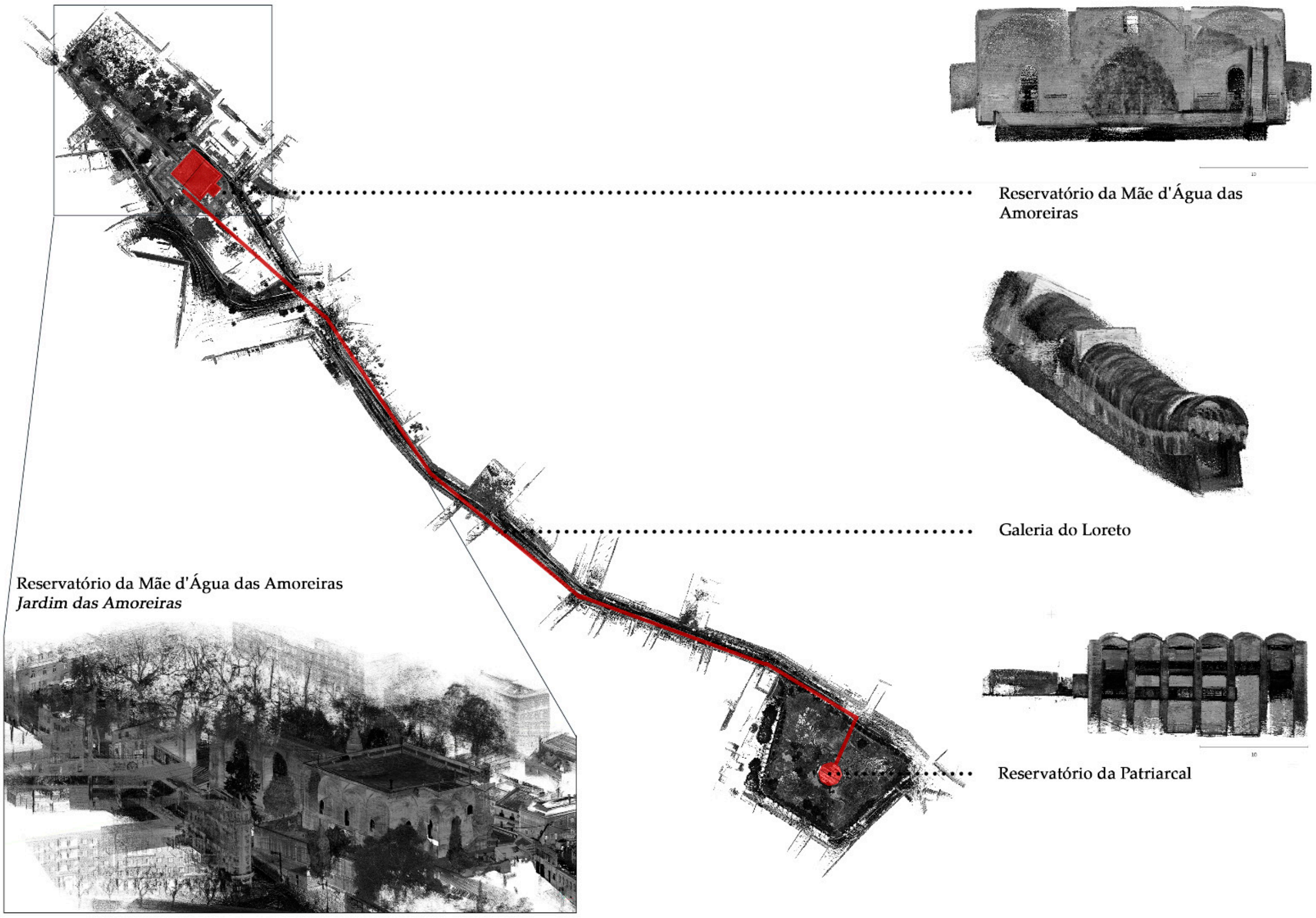
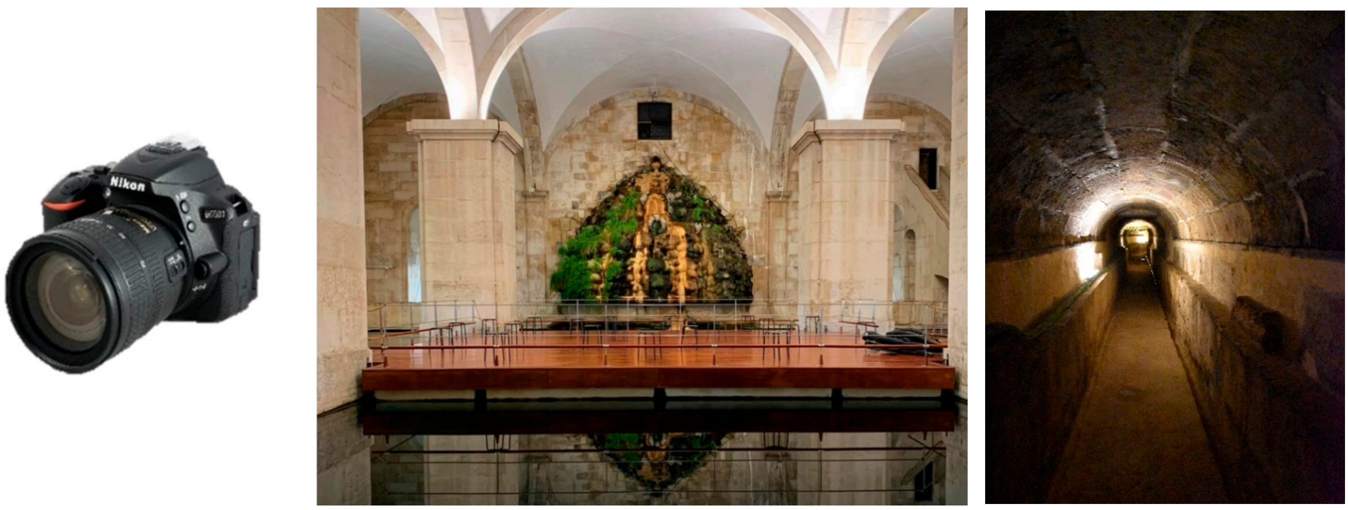


Figure 6. Overall view of point clouds (aligned) and sections of underground parts.

Laser scanner survey was accompanied by photographic acquisition of the entire route. The Nikon D5500 [44] camera was used to capture 800 images covering the three surveyed areas (Figure 7), and the use of the Nikon KeyMission 360 [45] made it possible to acquire video and spherical photos of the points of interest (Figure 8).



(**a**) (**b**) (**c**)

Figure 7. (**a**) Nikon D5500 camera; (**b**,**c**) Images captured with reflex camera.

(**a**) (**b**)

Figure 8. (**a**) Nikon KeyMission 360; (**b**) Image captured with spherical camera.

4. Results and Discussion

After the preliminary stages of research and data acquisition, followed by structuring of descriptive and historical data and processing of survey data, the collected data were processed for their integrated management in a GIS environment. Figure 9 shows the elaboration scheme of the 2D/3D models that will be illustrated in the following paragraphs (Sections 4.1 and 4.2).

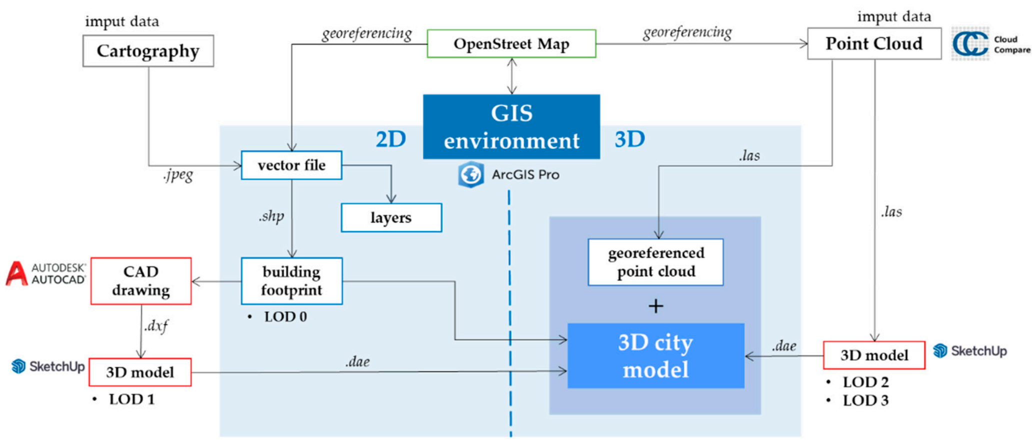


Figure 9. Elaboration scheme of 2D/3D model for GIS.

4.1. Data Management in 2D GIS

The historical cartography was used as a raster map and georeferenced in the adopted reference system, EPSG:32629 Pseudo Mercator. The process of georeferencing the raster image, representing the historical cartographic information, is carried out by means of geometric transformations and resampling through the identification of homologous control points identified both in the raster image and in today's vectorized digital maps with which the comparison is to be made. An OpenStreetMap base-map was used to obtain coordinates for georeferencing.

Subsequently, the georeferenced map was combined with a base map provided by ArcGIS Pro [46] to create a shapefile of the paths of the Aqueduto das Águas Livres and secondary aqueducts (Figure 10).

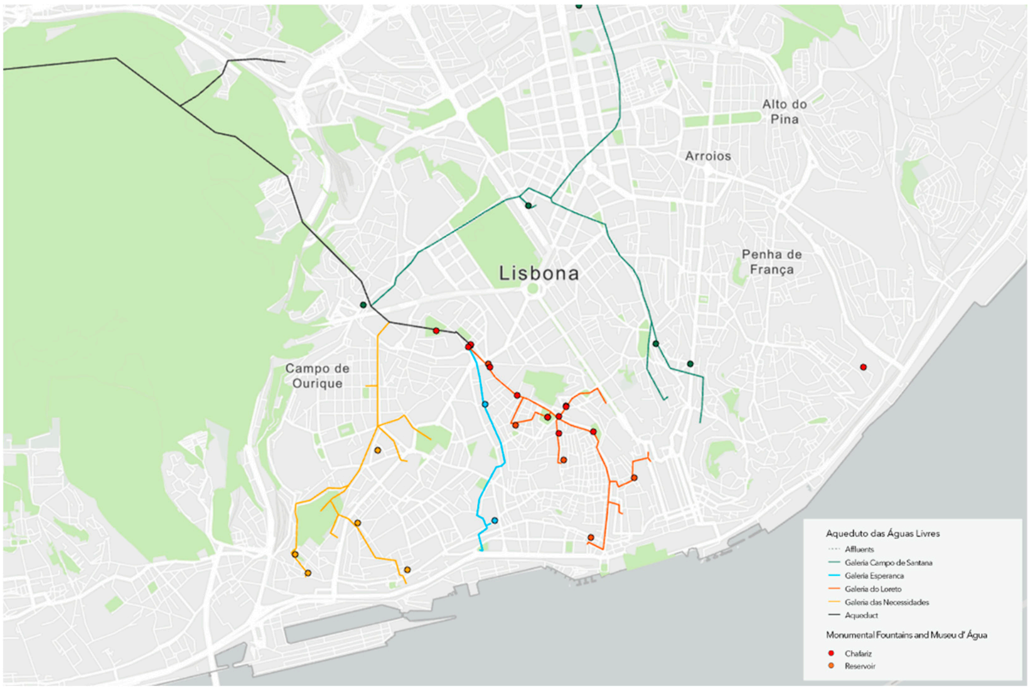


Figure 10. The 2D GIS map with layers of the Lisbon aqueduct system (Aqueduto das Águas Livres).

In GIS, the first step is the creation of shapefiles, i.e., layers containing the vector entities (points, lines, polygons) organized according to a Coordinate Reference System (CRS), which determines the real position of the object in space [47]. For each base-map layer, its attributes are displayed in an assigned table [48]. Each row, in the attributes table, represents an object (with or without geometry) and each column contains a piece of information related to the object, which is manually assigned to the features. Fillable fields were entered for: IDTYPE, NAME, LOCATION, DATE of construction, EXTENSION of the object (length for line and area for polygon), DESCRIPTION, IMAGE, and SHAPE of the layer (Table 5). The IMAGE entry containing a hyperlink to the external folder created on Google Drive with the images acquired during the survey.

Table 5. Database structure in SQL.

ID Type	Name	Location	Date	Extension	Description	Image	Shape
Numeric	Char(n) $1 \leq n \leq 254$	Char(n) $1 \leq n \leq 254$	Char	Char	Char(n) $1 \leq n \leq 254$	https:// *(link to external data)*	point, lines, polygons

After constructing the layer with the shape of the main buildings along the route of the Galeria do Loreto, Points of Interest (POI) were added manually (Figure 11). They represent a simple and accurate dataset suitable for populating the mapping project with places/points of interest. These POI can be used as the basis for most of the data supporting location-based applications: to generate the indoor network, to create categories and to make features searchable and explorable in Indoors web and mobile apps. Thus, through POI mapping, digital maps can be created that provide detailed route information with an image of the destination site.

Figure 11. The 2D GIS map with POI referring to Galeria do Loreto.

4.2. Data Integration in 3D GIS

Thanks to the survey carried out with the mobile mapping tool (Section 3.3), it was possible to realize the 3D features of the objects, which enable the information system to be enriched by developing a 3D GIS. The objective is to provide a 3D representation of the UBH in relation to the urban context where it is located and to provide a clearer visualization of the volumes describing the underground environment.

For this purpose, the cartography of the urban area and point clouds were used to model the 3D city objects. This modeling process was based on the logic of multi-scale representation based on the LODs of the OGC standard. The LOD 0 describes a landscape scale, the LOD 1 the city, the LOD 2 the city components, and the LOD 3 and 4 the architectural models (buildings), respectively, with the outdoor and indoor elements. If we consider some literature examples about point cloud classification in the geospatial field [49–52], we can assert that the level of detail reached is between LOD 2 and 3. Specifically, for this case study, it was decided to model (Table 3) the following:

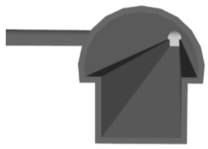
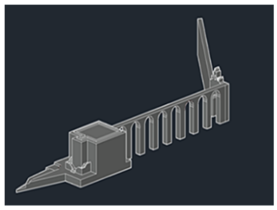
- Part of the urban context, in which these elements are located, at LOD0 and LOD1;
- Part of the underground tunnel of Galeria do Loreto at LOD2;
- The building of Reservatório da Mãe d'Água das Amoreiras at LOD3.

Regarding the realization of the volumes of the buildings in the urban context from LOD0 to LOD1, a simple extrusion of the footprints of the buildings provided by the cartographic 2D map was carried out where the known height of the buildings was taken into account (Table 6, Figure 12).

The volumetry of the tunnel was extracted using point cloud measurements. Given the difficulties in capturing the underground tunnel, an approximate parameterization was used. Modeling was also supported by the file of the paths, obtained during the mapping acquisition phase, exporting in .dxf format and subsequent import into the SketchUp software to complete the definition of the multipatches of the tunnel.

The processed data from the mobile mapping acquisition was useful to create the 3D model of the Reservatório da Mãe d'Água das Amoreiras. LOD3 was attributed to this building because, thanks to the laser scanner survey, which was carried out under conditions, that did not compromise the final result, it was possible to define its external volumes, from the walls to the roof, with the greatest level of detail.

Table 6. Definition of LODs of modeled objects for 3D GIS.

	LOD0	LOD1	LOD2	LOD3
Model scale	Landscape	City model	Building Model	Detailed Building Model
Model description	2D city plan with building footprints	3D space defined by the height of buildings and represented by different volume units.	Geometric model of the structure represents, schematically, the external or internal form.	Vertical development of the structure can be represented in an approximate manner, and the shape of roof is defined.
Representation scale	1:5000–1:2000	1:2000–1:1000	1:1000–1:500	1:500–1:200
Class of accuracy	Lowest	Low	Middle	High
Data input	Cartography	Cartography	Point cloud	Point cloud
Results				

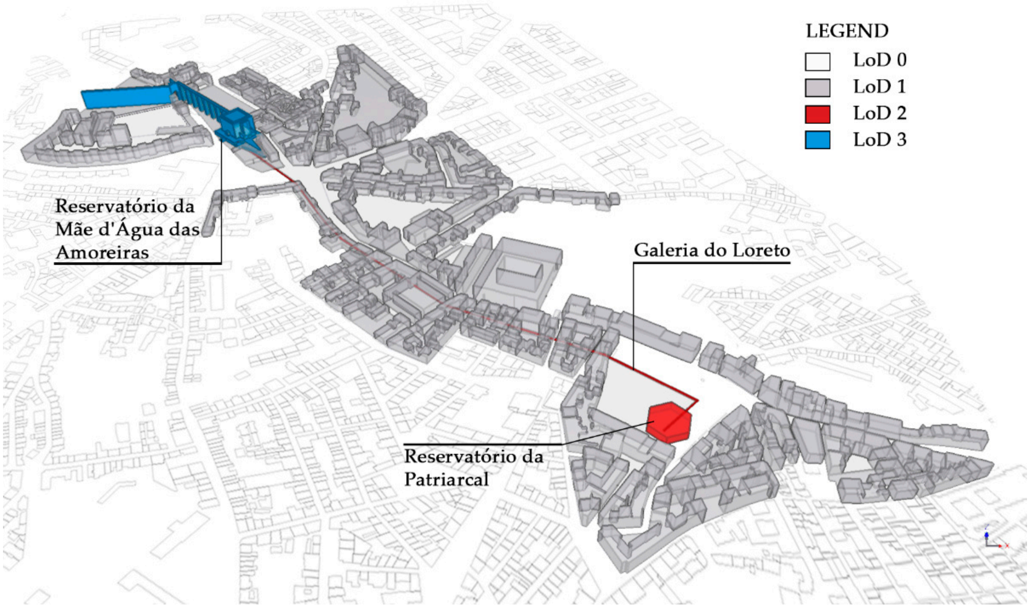
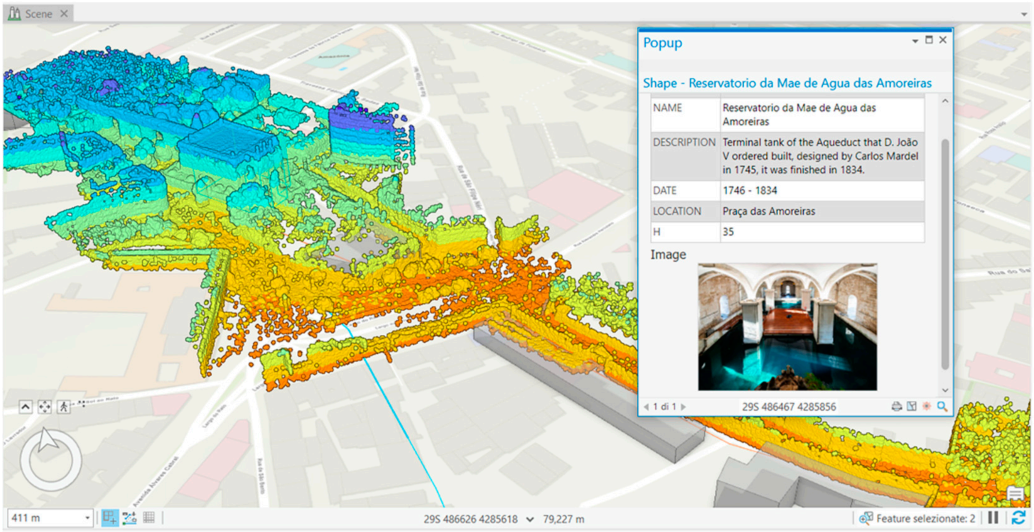


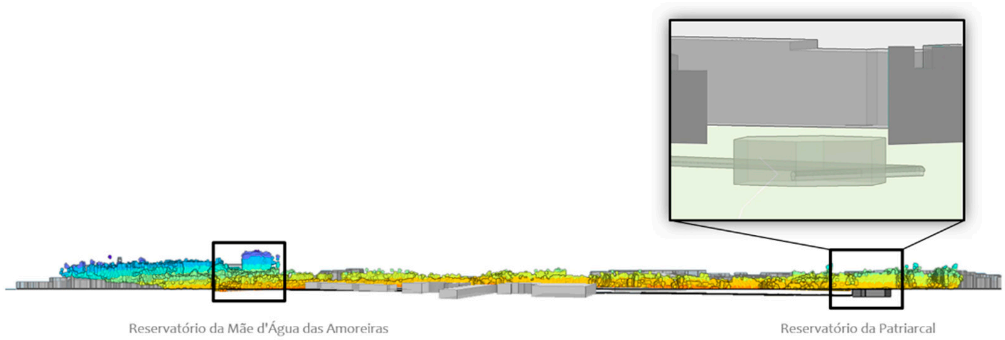
Figure 12. Representation of 3D model according to LOD classification.

Once the 3D modeling operation was performed, 3D models referring to the urban context and the Reservatório da Mãe d'Água das Amoreiras were imported into the SketchUp software and merged with the underground tunnel. In this way, in the GIS workspace, it is possible to have multiple layers of detail within a single project. The model was then imported in its entirety as a .kmz file into Google Earth to verify geolocalization, and finally imported into a 3D GIS (Arcscene software). Information entered within the GIS 2D can be implemented with the new information and linked to the 3D model.

In addition, the point cloud (.las format) of the whole context uploaded in integration with the 3D model, thus achieving complete data fusion (Figure 13).



(**a**)



(**b**)

Figure 13. Data integration of point cloud overlapping the 3D models in 3D GIS environment: (**a**) aerial view; (**b**) front view with zoom on the 3D model of part of the underground environment.

Thanks to ArcScene [46] functionalities, it is possible to query both the point cloud and the 3D model and obtain 2D and 3D information without having to switch between Map and Scene views. ArcGIS PopUps allow the activation of links to other content, so a hyperlink to the 3D model containing its display within the browser from Trimble Connect 3D Viewer [53] has been linked. This is a SketchUp extension that not only displays the 3D model, but also allows one to make sections of the model to better understand its distribution and adjust the view. Similarly, it is also possible to view the point cloud via Trimble. The latter makes it possible to display the 3D model created for data sharing purposes to figures outside the project who can freely access the virtual representation without the need for specific skills with GIS software.

4.3. Limitations of the Proposed Methodology

Although the solution proposed in this paper proved its reliability, as well as its usefulness for further smart cities scenario, it is fair to highlight its limitations. It is the opinion of the authors that the weakness points lie on three main aspects, namely, the replicability, the UBH data collection, and the simplifications operated to move from different LODs. Despite the integration from different data sources can be easily managed in the GIS, this operation is still entrusted on manual operations and on the data availability from the municipalities (e.g., cadastral sheets); this represents a bottleneck worldwide, and as long as the information is updated, the interoperability among heterogeneous information still remains a con, hampering the full replicability in other contexts. Another important aspect to be highlighted is that surveying UBH requires a superior degree of complexity that are not present in common scenarios. This means, as demonstrated in Section 3.3, that to achieve a comparable degree of detail and accuracy, the instrumentation to be used are different, and not always possible to merge. As such, the utilization of mobile systems can be a viable alternative, but more efforts are needed in developing low-cost strategies for the amalgamation of indoor/outdoor settings. Consequently, the management of different LODs becomes paramount; however, the current state-of-the-art solutions do not provide a dynamic way to implement LODs in a more flexible way. Being rigid, the different scales of representation required for the multifaceted urban settings hamper the full integration of the data sources.

5. Conclusions

Underground Built Heritage is a cultural resource that can contribute to individual and collective identity, social cohesion, and social development, as they can be at the core of a community's sense of belonging. For this reason, filling knowledge gaps and making digitally visible such underground landscapes are major challenges.

The described study demonstrates how innovative 3D surveying technologies, such as MMS, integrated with information management system, such as GIS, can be effectively used to explore and map comprehensively this UBH. To ensure a better understanding of the data and the relationships between the surface and beneath it, it was considered necessary to implement the GIS with spatial information. Therefore, the study was not limited to the management of 2D information but set as main objective to create a 3D GIS that would ensure the management of the collected data, acquired and its consultation and implementation, making it remotely accessible and understandable to the local community.

For the creation of a 3D model based on point clouds from MMS acquisition, a method of data management and processing was applied, which allowed to show the limitations and problems of 3D digitization of UBH.

Moreover, due to its enormous potential, the use of digital technology is now an essential step for all those working in the field of cultural heritage documentation and representation. The considerable amount of information acquired, stored in the digital model, offers an alternative approach to traditional research methods that aim to penetrate the complexity of cultural heritage by understanding all its perceptual and material values and qualities. In this context, the processing of the data obtained during the survey campaign led to the creation of a point cloud, which has a fundamental role both in documenting the state-of-the-art and in the analyses to be carried out. In fact, the resulting dense cloud forms the basis for the visualization and construction of a 3D model.

The counterpart of this approach, as broadly described in this paper, still remains the data exchange between information systems, still representing a major challenge. To cope with this limitation, an open-source platform based on three main technologies is currently being developed. This platform, which paves the ways for future implementations, would make it possible to (i) connect Building Information Models to external data sources, (ii) open the models to new use cases and applications, and (iii) automatically link survey results to related BIM elements using Web of data technologies.

This would make it possible to interoperate data into a unified model and achieve better information modeling for the UBH; nowadays, the use of fast and agile tools like MMS (SLAM based) and or 360° allows to produce accurate 3D representation, but unordered and unstructured. The path toward a full exploitation in a more readable 3D format is far, but future efforts will make the process more straightforward, even considering the introduction of Artificial Intelligence in the loop.

Finally, it could be a way to effectively provide information to stakeholders, as the platform allows data to be published on the Web, interacted with, updated, or deleted, thus also contributing to appropriate urban planning.

All in all, the studies carried out stand as a starting point for future developments, and the methodology used for its implementation can be considered a solid basis for future surveys. Thus, the study is representative as a paradigmatic example of how technological developments can make people's lives smarter and more connected to their own heritage, especially where the urban layout is not inclusive for the more conceived, but as well important, as UBH is. This is a win–win situation, for Lisbon to have such treasure revealed and the COST Action Underground4Value to count on a tested and replicable work methodology that provides the needed information to bring an UBH asset to the core of the community.

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Data Availability Statement: The publicly available dataset analyzed in this study is the final 3D model shown in Figure 9. This data can be found at: https://3d.connect.trimble.com/?projectId=bh5ZdCvcNT8&modelId=JHNoSnXvHZA&=&origin=app.connect.trimble.com&stoken=XJzWGNBNlluBqtJeu_XAwhYJM7WzU53bFloPQJqpokAyf-ygfWnjoZnu7ir9Hfmv (accessed on 25 June 2022).

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