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NDT spatial data integration for monumental buildings: technical information management for the Royal Alcazar of Seville

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ABSTRACT

Non-destructive testing (NDT) for the diagnosis of heritage buildings has proved to be one of the most sustainable approaches in the field of preventive conservation. Nevertheless, the comprehensive management of NDT information is complex, often resulting in a poorly optimized use of the data. This contribution aims to propose a method for integrating NDT data in a standardized way into simplified digital information models, produced using Geographic Information Systems (GIS). This method is applied to the plasterwork located in the Courtyard of the Maidens, which are elements with an enormous historic-artistic value in the Royal Alcazar of Seville (Spain), a significant UNESCO monument. For this purpose, a multi-scale web GIS-based model has integrated the NDT information from the plasterworks, such as ambient conditions, damage mapping, C-Shore Hardness, Superficial Humidity, Infrared thermography (IRT), Digital Image Processing (DIP) and Ground Penetration Radar (GPR). The combined georeferencing of the data from the various measurements and their simultaneous visualization has enabled the detection of vulnerable areas in the complex. The results are easily accessible for managers, and additionally show the analytical potential of the research approach, thereby allowing a quick diagnosis and hierarchization of tasks.

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Geographic information systems (GIS); standardization; Mudejar architecture; preventive conservation; architectural heritage; non-destructive testing

Introduction

The preservation of historic buildings with a pronounced heritage character constitutes a major challenge. It must therefore be approached from different perspectives (Lobovikov-Katz et al., 2018). Today, the integration of all such disciplines finds a fundamental partner in digitization, and its use is highly encouraged at the governmental level (European Commission, 2019, 2021). In particular, 2D–3D digital information models are proving to be useful tools for heritage conservation (Xiao et al., 2018).

State of art

There are many contributions in this field, with a pre-eminence of methodologies based on the use of Building Information Modelling (BIM), particularly Historical BIM (HBIM) on an architectural heritage scale (Sumeyye Sena Bastem & Cekmis, 2022; Yang et al., 2020). Alternatively, the use of Geographic Information Systems (GIS) in the field of heritage conservation (Ferreira-Lopes, 2018) was limited to the study of larger-scale contextual factors (Agapiou et al., 2015), and there is a growing trend towards taking advantage of the benefits of HBIM-GIS workflows (Chenaux et al., 2019; Colucci et al., 2020; Ramírez Eudave & Miguel Ferreira, 2021). Nevertheless, in recent years, the implementation of GIS on a detailed architectural scale in the field of heritage is gaining a foothold (Campanaro et al., 2016; Ivan Apollonio et al., 2018). The powerful capacity to manage spatial databases of different formats provided by GIS allows the analysis and web-publication of technical parameters, monitoring and damage diagnosis, among other activities (Campiani et al., 2019; Iandelli et al., 2021). These qualities are particularly useful in the field of preventive conservation, considered the most efficient approach for protecting heritage sites (Kutasi & Vidovszky, 2010; van Balen & Vandesande, 2013).

The effective implementation of preventive conservation measures requires the use of standardized procedures for the documentation, management, consultation and updating. Recent examples, such as

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the European Heritage Care project (Sánchez-Aparicio et al., 2020), take advantage of these possibilities by proposing holistic procedures to increase knowledge of built heritage between the participants involved (both expert and non-expert users). Likewise, other contributions with a specific ontological-based approach to optimize the information management processes have also become relevant (Zalamea Patino et al., 2018). Its implementation in digital information models establishes a powerful framework for the components of the managed data (Acierno et al., 2017; Messaoudi et al., 2018).

It should be borne in mind that the accuracy provided by the new digital tools and the 3D models generally require the availability of human, material and economic resources. When this circumstance is unfeasible, it is considered necessary to propose automatic (Swaileh et al., 2022) and semi-automatic procedures (Hidalgo-Sánchez et al., 2022). Consequently, this research assumes such an approach, and relies on the knowledge structures proposed and validated in previously cited investigations.

Concerning the field of preventive heritage conservation, the use of Non-Destructive Tests (NDT) has proven to be a necessary resource for the protection of cultural heritage, ranging from decay diagnosis to monitoring (Tejedor et al., 2022). Procedures, such as Damage Mapping (Sánchez-Aparicio et al., 2018), measurement of C-Shore Hardness (Blasco López & Alejandre Sánchez, 2013) and Superficial Humidity (Battini & Vecchiattini, 2018), Infrared Thermography (IRT) (Moropoulou et al., 2018), Digital Image Processing (DIP) (Galantucci & Fatiguso, 2019), Ground-Penetrating Radar (GPR) (Ortega-Ramírez et al., 2021) and monitoring of ambient conditions (Merello et al., 2013), provide reliable means of assessing damage to heritage assets. Moreover, these methods function without compromising their structural condition and help to identify hidden targets that are invisible on the surface (Biscarini et al., 2020; Diz-Mellado et al., 2021). Once the data has been acquired through NDT surveys, a management programme for future interventions can be defined (Kilic, 2015). The contributions made to date in the implementation of information from NDT in GIS environments for heritage are mainly focused on damage mapping (Canciani et al., 2013; Günay, 2012; Kukela & Seglins, 2013; Stefani et al., 2014), and fail to take full advantage of the analytical capabilities of GIS tools. Certain recent examples, such as the Chisel (F. Soler et al., 2013) or Agata software (Francisco Soler et al., 2017), represent an advance in the possibilities of analysis, but they lack the versatility currently offered by cloud-based applications to generate an efficient collaborative work environment. Likewise, the construction of an active database that includes the time variable as a fundamental parameter for the control of risks and damage has yet to be sufficiently developed. Contributions, such as that of López González (2015), have striven to include this variable with interesting results that demonstrate the usefulness of this type of approach, but have found limitations in the information processing capacity of the GIS tools used. It should also be noted that practically all these proposals use clouds of points obtained through laser scanning or photogrammetry, which serve as a reference for 3D modelling. Hence, the importance of 2D–3D modelling capable of adjusting to the purposes pursued.

Research hypotheses and objectives

The objective of this research is to generate a procedure to integrate different NDT data into a GIS database that is both two- and three-dimensional. This data can also be shared with different levels of openness on a GIS cloud platform, ranging from open data for public dissemination purposes to restricted use for internal information management. In particular, the spatial database proposed has the following properties: active (allowing the constant updating of information); adaptive (including information of a different nature and format coming from tests and inspections); normalized (taking into account the terminological, thematic and spatial components involved in the heritage discipline from a technical perspective); geo-referenced (using simplified 2D–3D digital information models as a graphic base); and interactive (allowing the consultation and exchange of information between different agents).

The implementation of this workflow is tested on a case study of Spanish architectural heritage: the Courtyard of the Maidens of the Royal Alcazar of Seville (RAS). Although the spatial database considers the RAS in a multi-scale manner, in this contribution it has been studied in depth the plasterwork of the Courtyard. These decorative elements are of great historical-artistic relevance, and it is necessary to monitor and control them over time in order to facilitate their preventive conservation, minimize the potential risks and guarantee their preservation. This information constitutes an essential part of the geo-referenced database proposed by the research. Linking the spatial features representing the architectural elements to the corresponding documentary and alphanumeric information offers the possibility of conducting powerful statistical analyses in a graphical and dynamic way. Thus, the spatial component has proved to be extremely useful to deal in a comprehensive manner with the complexity inherent in such a varied volume of information.

By taking the aforementioned aspects into account, this document is structured as follows: a brief description of the case study; the methodological approach corresponding to the proposed procedure; and the discussion of the results. Finally, the main conclusions drawn during the research itself are laid out.

Case study

The RAS is a palatine complex whose construction began in the 11th century (Tabales Rodríguez et al., 2017), in which the Palace of Pedro I (1356–1366) stands out (Almagro Gorbea, 2007). The cultural and architectural importance of the monument was clear in 1987, when the UNESCO declared the entire complex of the RAS a World Heritage Site (UNESCO World Heritage Committee, 1987).

Over the last decade, the managers of the RAS have been working on the development of the Restoration Management Plan, the Preventive Conservation Plan and its own management system (García, 2020; Muñoz García & Atanasio Guisado, 2015; Rodríguez Rodríguez, 2019). This research should serve as a useful complement to address the needs of the monument, especially in the field of digitization and its application to the conservation of the complex.

In particular, the Courtyard of the Maidens (14th century) constitutes one of the most representative spaces of the Palace of Pedro I (Figure 1). This space has undergone major modifications in its morphology since its construction (Tabales Rodríguez, 2005), whereby elements of its original configuration have been recovered in recent years (Almagro Gorbea, 2005). Its plasterwork decorations present the worst state of conservation of all those existing in the RAS (Serrano Rodríguez, 2019), and have been the target of multiple conservation actions. This is mainly due to three reasons: (i) the effect of environmental conditions, especially the presence of humidity, which influences the expansion and/or oxidation of embedded metallic elements; (ii) the numerous interventions that have been carried out throughout history in this area without following current restoration criteria; (iii) the anthropogenic factor, given that some of the plasterwork is at a lower level, thereby enabling its accessibility and possible manipulation (Troitiño Vinuesa et al., 2020).

In this regard, plasterwork located in the Courtyard usually presents anomalies of a different nature. On the one hand, there are structural and constructive anomalies, which imply a risk to its durability (e.g. lack of adhesion, cracks, fissures and detachments). On the other hand, there exist aesthetic and visual anomalies (e.g. disintegration of the material, efflorescence and cryptoflorescence, oxidation, colour changes, biological colonization and biodeterioration, and dirt accumulated on the surface). Hence, the preventive conservation and maintenance of the plasterwork, and the programme of actions for its preservation were recently undertaken (Campos de Alvear, 2020b). Furthermore, experts in the field of restoration continue to gather information through careful organoleptic inspections and NDT. From among the work carried out in recent years, the following in Table 1 have been considered for this research.

This work proposes georeferencing the plasterwork of the 0.60 m-wide frieze that decorates the perimeter

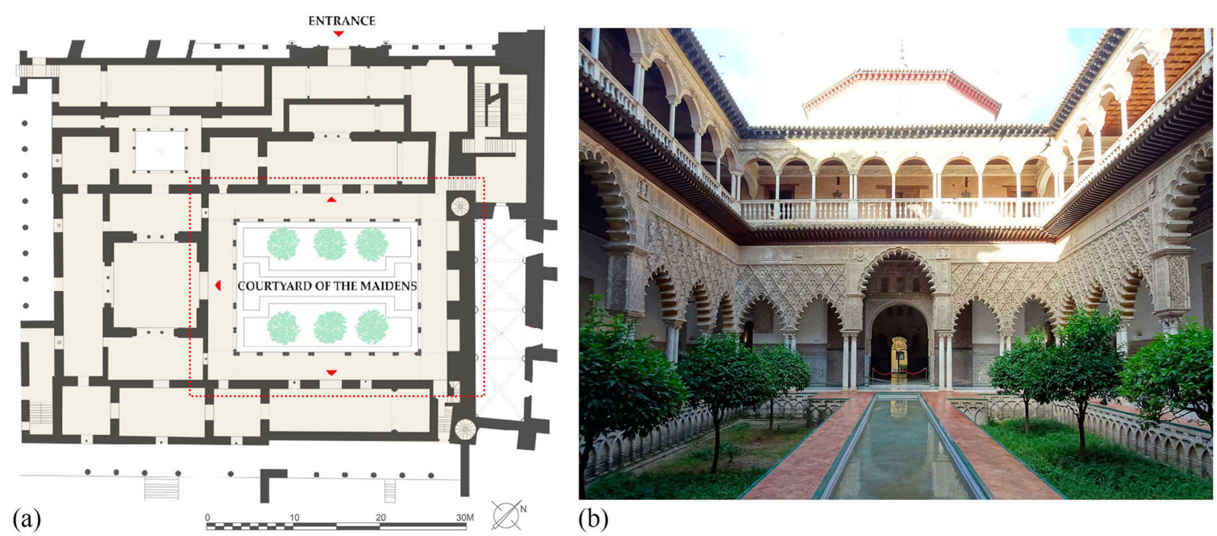


Figure 1. Ground floor of the Palace of King Pedro I showing the location of the Courtyard (a). Current state of the Courtyard (b).

Table 1. Recent work in plasterwork.

Identification	Reference
Planimetric survey	Gorbea (2003)
Physical–chemical characterization	Calero-Castillo et al. (2016)
Determination of the conductivity humidity in plasterwork	
Re-creation of the colour in the plasterwork using virtual palettes	Coba Peña et al. (2016)
Analysis of the limewash	Alejandre Sánchez et al. (2021)
Measurement of plaster thickness, polychrome and whitewash	
Measurement of the width and depth of cracks and fissures	Campos de Alvear (2020a)
Localization of the cavities by means of a rubber hammer or GPR	Torres-González et al. (2021)
C-Shore surface hardness test	
Detection of metallic elements and study of its corrosion	
Thermographic imaging	
Measurement of ambient conditions	
Photogrammetric survey	Cabrera-Revuelta & Aguilar-Camacho (2022)

of the galleries of the Courtyard at a height of 1.80 m above the level of the flooring (Figure 2). According to Pavón Maldonado (1973), this frieze corresponds to 14th-century Sevillian plasterwork, with the exception of the zones 08, 10 and 12, which are from the 19th century.

The frieze under study is composed of a motif that is repeated along the perimeter of the Courtyard (Rubio Domene, 2010). It consists of medallions with heraldic emblems, bands with epigraphic motifs and geometric decorations (Figure 3).

Methodology

This section presents the proposed procedure for the integration of NDT data for the management of heritage buildings in GIS environments. The method is experimental and has been implemented in a case study that includes a final validation process, making it possible to generate a procedure that is defined in the following phases (Figure 4). The first phase includes detailed information on the tests carried out. Secondly, through a process of standardization according to terminological, thematic and spatial fundamentals, the information is processed and incorporated into the database (Data Processing). A protocol is subsequently established to create a geo-referenced 2D and 3D model of the case study that provides the graphical and spatial dimension to the semantic information collected (Data Modelling). Finally, the results obtained are published as open data in a GIS Cloud environment to render it available to a wide range of users (Output Data).

Input data: diagnosis data collection

The following NDT were considered to evaluate the state of conservation of plasterwork (Figure 5).

Damage mapping

Considering the in-situ inspection, a damage mapping can be drawn to show the main anomalies per zone,

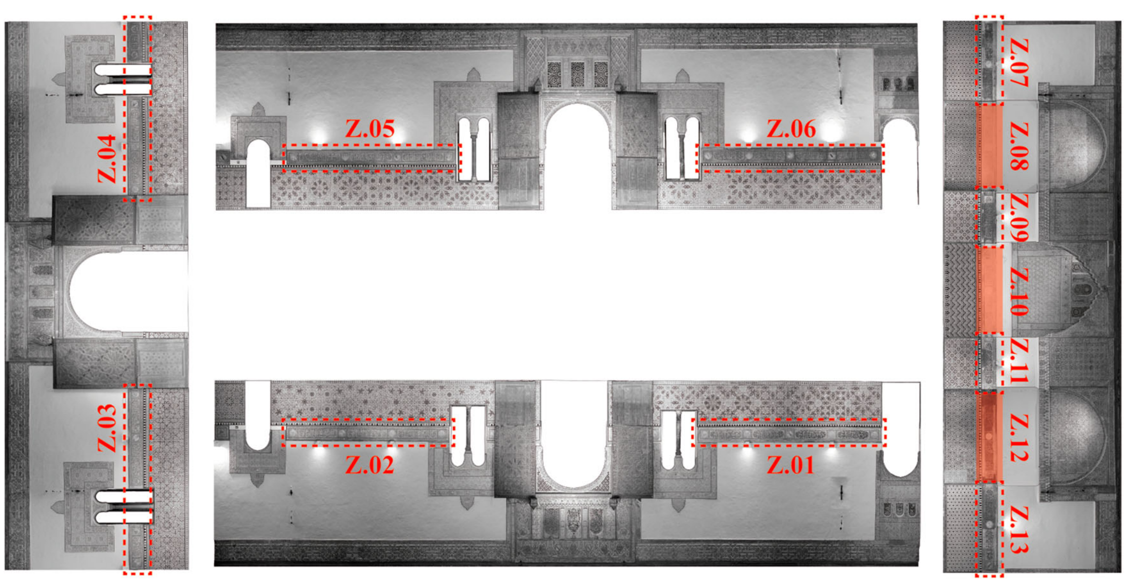


Figure 2. Perimeter galleries of the Courtyard: Location and zoning of the study areas.

Figure 3. Elemental unit of the frieze under study (Z.01).

thereby attaining a data record. This is especially interesting when monitoring of the degradation situation (e.g. in the case of fissures and cracks, it is possible to monitor their length or weight once this information is included in the database). Scaled planimetry has been introduced in the spatial database with the representation of the alterations.

Mechanical properties: C-Shore hardness and superficial humidity

The measurement of mechanical properties is necessary to ascertain the inner stability of the plasterwork and its weakening. According to UNE-EN 102042 Standard, UNE-EN 16682 Standard and to the guidelines exposed by Torres-González et al. (2021), the C-Shore hardness and superficial humidity are measured by using a conductivity moisture meter and a durometer (AENOR, 2014, 2018; Torres-González et al., 2021). It is highly recommended to take all the measurements at the same points to guarantee the correlation between the two sets of results.

Previous work yielded C-Shore hardness values between 67 and 83 units (Torres-González et al., 2021), and the minimum values of C-Shore surface hardness for plaster coatings are set at 45 units in the case of traditional plaster (Villanueva Domínguez & García Santos, 2001), whereby values greater than 45 C-Shore units are considered to be admissible. In relation to moisture measurements, previous work stated that the slight hygroscopicity of the gypsum is relevant when plasterwork is exposed to high levels of relative humidity, namely 95%. Exposure to relative humidity below 65% is recommended to avoid the weakening of the crystalline structure of the plaster, which could lead to the proliferation of micro-organisms and biological agents (Freyer & Voigt, 2003; Ritterbach & Becker, 2020; Torres-González et al., 2021). The values obtained from the two

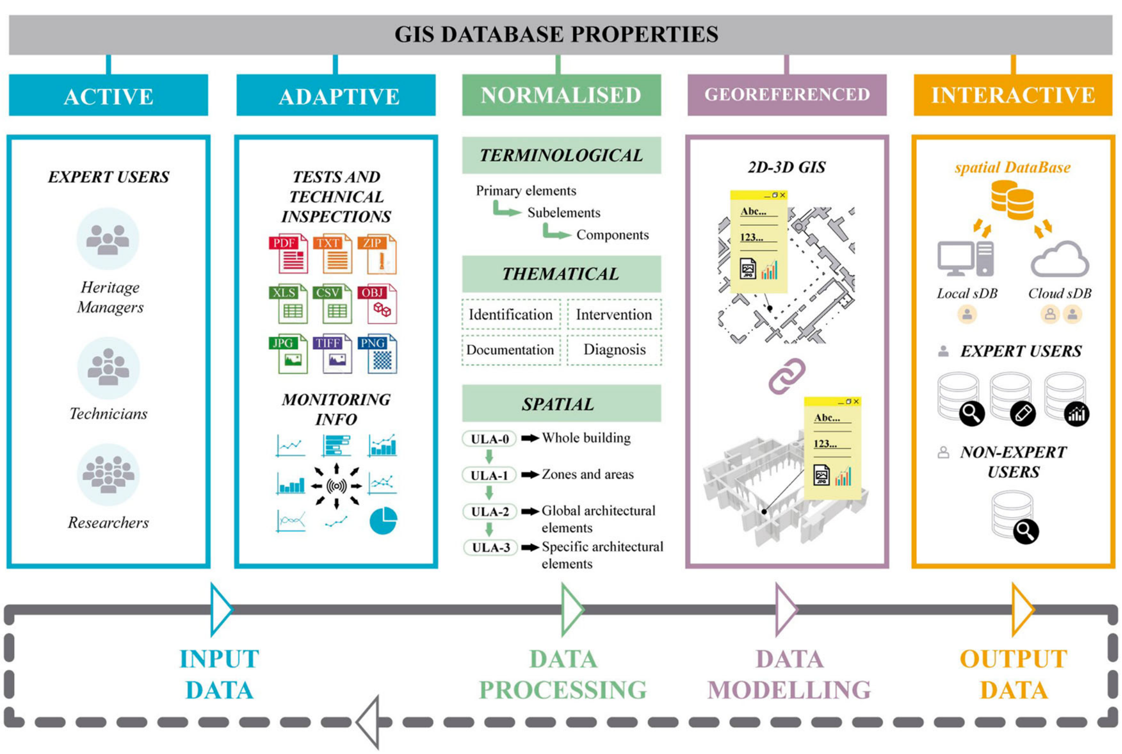


Figure 4. Integrated NDT-GIS global methodological process.

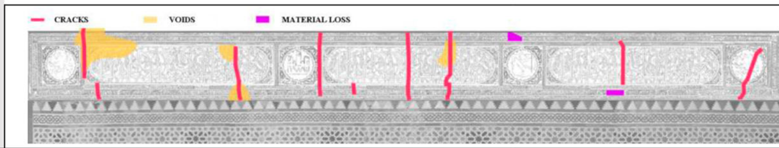
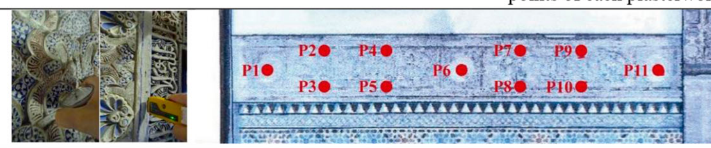
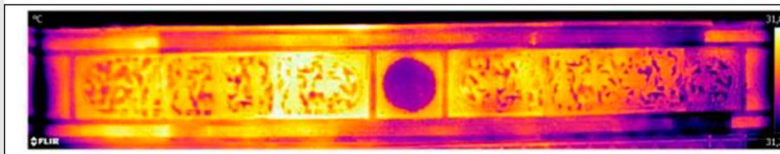
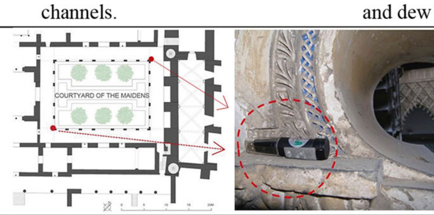
NDT	Tools and software used	Results included in the DB
Damage mapping	On-site drawings and AutoCAD v.2021 software.	Damage maps.
		
C-Shore Hardness & Superficial Humidity	Bareiss Type HPE II DGM 9318389.5 Shore durometer.	Measurements taken at different points of each plasterwork.
		
Infrared thermography (IRT)	Thermal FLIR T840 camera [thermal sensitivity of <30mK at 30°C (42° lens); resolution of 928x696 pixels]. Flir Tools and ThermaCAM Researcher Pro-2.10 software.	Thermographic images with different filters.
		
Digital Image Processing (DIP)	Nikon D3300 camera [24.2 MP DX format CMOS (23.5x15.6 mm)]. Agisoft Metashape Professional software v.1.7.1.	Photogrammetric models.
		
Ground Penetration Radar (GPR)	GPR model GP8800 manufactured by PROCEQ [defined frequency range: 400-6000 MHz; penetration capacity ≤ 65 cm]. Data processed using Proceq GPR Live software.	Radargram readings.
		
Monitoring of ambient conditions	EL-USB 2 LCD thermohygrometer with two registration channels.	Temperature, relative humidity and dew point data collected.
		

Figure 5. NDTs carried out in friezes with detailed information.

tests have been entered into the spatial database as alphanumeric information, whereby values between 1 and 100 C-Shore hardness and 1–100% of moisture content are considered.

Infrared thermography (IRT)

This technique allows the detection of discontinuities, possible non-visible detachments in claddings, and the presence of moisture by representing apparent surface temperatures (Adamopoulos et al., 2020; Costanzo et al., 2015; Grinzato, 2012; Tormo Esteve, 2016). The thermographs obtained from the plasterwork are linked with their corresponding element in the geo-referenced model as searchable images, detailing the date and exact time of capture.

Digital image processing (DIP)

In several aspects, photogrammetry has proved to be a potential tool in its application to historic plasterwork. Firstly, it favours the dissemination of models and geometries of great historic-artistic value, allowing reconstructions of the original designs and of the polychrome finished in the different periods (Ávila Rodríguez, 2019; Norin et al., 2019). Furthermore, it quantifies the disturbances present (e.g. slumps, cracks, loss of mass and/or colour) and allows them to be tracked by superimposing clouds of points taken on different dates. Finally, it helps digital registration of areas that are difficult to access, thereby saving money and time, since the models can be consulted from the virtual database. The proposed spatial database includes web links to view high-resolution photogrammetric surveys of the friezes in an online repository.

Ground penetration radar (GPR)

GPR is a NDT that uses UHF (ultra-high frequency) electromagnetic waves designed to detect non-visible properties following the principle of wave reflection in dielectric discontinuities. Its functionality has been proven useful regarding plasterwork (Torres-González et al., 2021), revealing the presence of metal fixings and voids. The radargrams obtained are included as a graphical input data in the spatial database.

Monitoring of ambient conditions

Environmental parameters exert a direct influence on the preservation of plasterworks. The presence of water constitutes one of the most negative factors for its conservation, and therefore monitoring the parameters of temperature and relative humidity through sensors or thermohygrometers is advisable in order to take the appropriate palliative measures (Torres-González et al., 2021). The data included have been taken by two sensors located at the north and south corners of the Courtyard, at a height of 3.00 m, from October 2020 to March 2022, with data collected hourly. This data is included in the spatial database and used in analysis and graphs to monitor the evolution of these parameters within the GIS environment.

As can be observed, each of these inspections and tests use different tools and materials, and deliver results in different formats (i.e. numerical, statistical or graphical virtual results). These considerations are taken into account for their subsequent inclusion in the spatial database.

Data processing: spatial database standardization

The spatial database must be built on the basis of an elaborate process of standardization of the information included therein, by addressing its terminological, thematic and spatial components. This section includes the conceptualization of this standardization process and its specific development for this case of study.

Terminological standardization

A glossary of architectural, constructive and spatial components allows the definition of a terminological standardization for the subsequent completion of the database. This contribution is focused on the initial typological definition of the architectural components, based on the specialized thesaurus of the Andalusian Historical Heritage (Junta de Andalucía, 1998). It is used for the different primary elements, sub-elements and components included in the glossary (Table S2 – Online supplementary material). Each of the features defined is given a specific code, which becomes part of the global coding that each feature receives according to the established spatial standardization. Figure 6 exemplifies the terminological definition of the elements located in the perimeter galleries of the Courtyard.

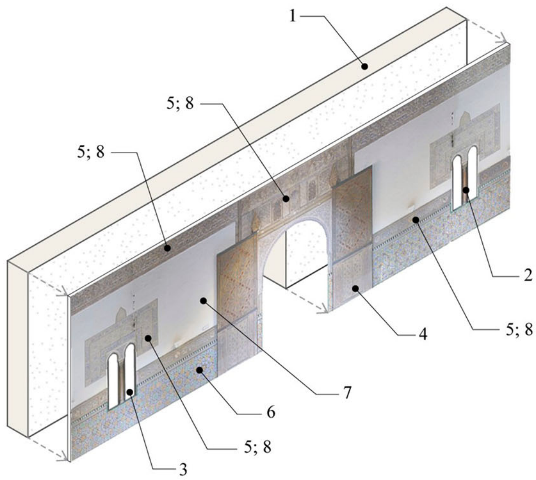
Thematical standardization

The objective of the thematic standardization is to define and categorize the different fields that comprise the database. The design of these categories aims to provide a multidisciplinary approach capable of including attributes that are not always considered when dealing with the physical conservation of a heritage asset.

According to the standardization criteria, the database is organized into four major categories of information: (A) Identification, (B) Documentation, (C) Diagnosis and (D) Intervention. These categories are detailed according to specific blocks and sections (Table S3 – Online supplementary material). Focusing on the purpose of the contribution, the 'C.1. Conservation' block, within the '(C) Diagnosis' category has been defined (Figure 7). In particular, a detailed configuration of the NDT content from the 'C.1.3. Active follow-up' section has been generated.

Nineteen fields have been configured to introduce contents from the sources and formats frequently used in this type of work, which facilitates systematized technical evaluation. Likewise, these attributes have been designed to optimize database management, enabling both the establishment of filters and spatial queries based on the defined fields and their content.

The information fields are shown by their original coded field name, used to generate the database, followed by their 'alias' in parentheses, which is the display name of the field. The code used responds to the following criteria, whereby the field 'DG_COFU_MOTG_X' is taken as an example (Table 2).



Primary element	Sub-element		Component
Structure (ES)	Vertical Structure (v)	1	Wall (-m)
		2	Column (-c)
Vertical hollow wall (CH)	Carpentry (c)	3	Window (-v)
		4	Door (-p)
Coatings, finishing and decorative elements (RA)	Vertical face (p)	5	Plasterwork (-y)
		6	Tiles (-a)
		7	Continuous cladding (-c)
		8	Polychromy (-p)

Figure 6. Identification of elements based on the established terminological standardization.

Spatial normalization and feature coding

Spatial standardization provides a set of basic graphical units of geo-referenced information, enabling the elements to be defined from the urban scale to the architectural detail. The different levels of detail are made up of Units of Logical Analysis (ULA), which gradually vary the precision of the information provided. Four levels of detail are established (ULA-0 to ULA-3), from the less to the most level of detail (Figure 8). A correlation is established between the different levels of detail, linking the architectural components to the areas in which they are located. Thus, the definition of zones established in ULA-1 is taken into consideration to identify the architectural components of ULA-2 and ULA-3.

- *ULA-0. Monument (_SERA)*. This represents the architectural complex as a whole. An identification is made by the acronym of the municipality where it is located, 'Seville, SE', and of the case study itself,

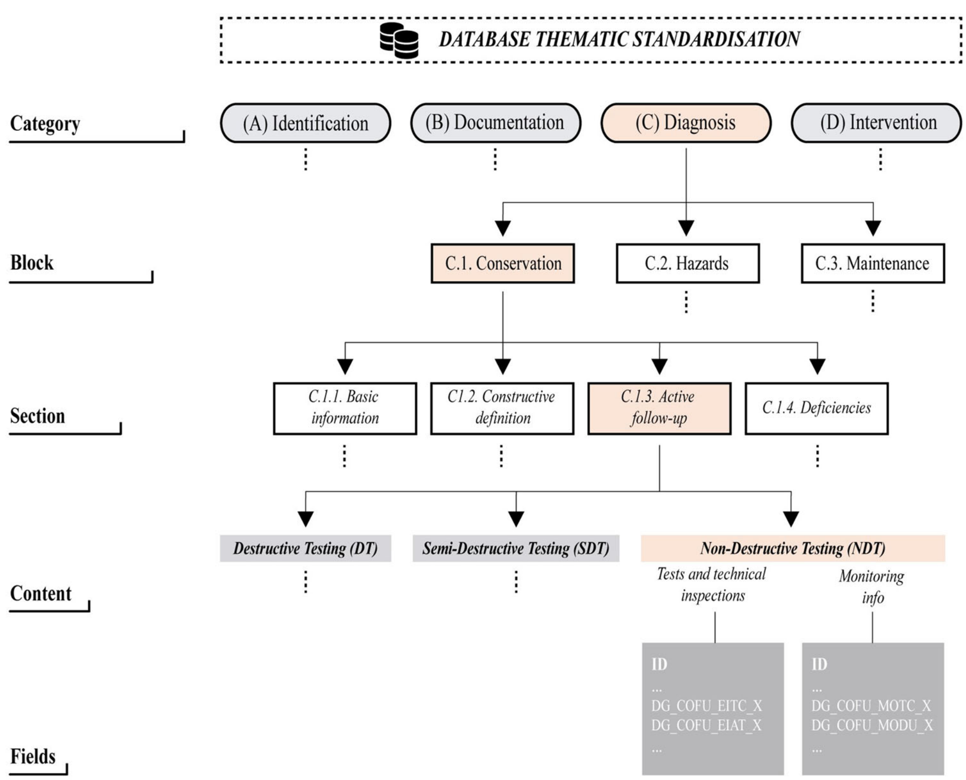


Figure 7. Thematic structure of the proposed database contents.

Table 2. Information fields defined for the 'C.1.3. Active follow-up' section.

Tests and technical inspections		Monitoring	
Field name (Alias)	Data (Type)	Field name (Alias)	Data (Type)
DG_COFU_EITC_X (Technique of test/inspection)	Standardized denomination (Text)	DG_COFU_MOTC_X (Technique of monitoring)	Standardized denomination (Text)
DG_COFU_EITG_X (Target of test/inspection)	Purpose and parameters analysed (Text)	DG_COFU_MODU_X (Duration of monitoring)	Period of time and specific details (Text)
DG_COFU_EIAT_X (Author of test/inspection)	First name initial and Last name (Text)	DG_COFU_MOTG_X (Target of monitoring)	Purpose and parameters analysed (Text)
DG_COFU_EIDT_X (Date of test/inspection)	mm/dd/yyyy -required-; hh:mm:ss -supplementary- (Date)	DG_COFU_MOAT_X (Author of monitoring)	First name initial and Last name (Text)
DG_COFU_EIVC_X (Characteristic Values)	Values obtained (Numerical, Short Integer)	DG_COFU_MOEQ_X (Tools and equipment)	Materials and resources used (Text)
DG_COFU_EIEQ_X (Tools and equipment)	Materials and resources used (Text)	DG_COFU_MOLK_X (Link of monitoring)	Supplementary data (Online; PDF, CSV, TXT, XLS, OBJ format)
DG_COFU_EILK_X (Link of test/inspection)	Supplementary data (Online; PDF, CSV, TXT, XLS, OBJ format)	DG_COFU_MOIT_X (Image/graphic title)	Standardized title (Text)
DG_COFU_EIIT_X (Image/graphic title)	Standardized title (Text)	DG_COFU_MOIM_X (Image/graphic)	File path (Raster; JPG, TIFF, PNG format; 200 × 150pp)
DG_COFU_EIIM_X (Image/graphic)	File path (Raster; JPG, TIFF, PNG format; 200 × 150pp)	DG_COFU_MOIC_X (Image/graphic caption)	Complementary details of the image (Text)
DG_COFU_EIIC_X (Image/graphic)	Complementary details of the image (Text)	-	-

DG(Category, *Diagnosis*)_**CO**(Block, *Conservation*)**FU**(Section, *Active follow-up*)_**MO**(Content, *Monitoring*)**TG**(Field/Attribute, *Target*)_**X**(Differential coding character for each type of test, inspection or monitoring info collected, *1,2,3, … ,n*).

'Royal Alcazar, RA'. Basic information corresponding to (A), (B), (C) and (D) thematic categories is available at this level.

- *ULA-1. Areas (_SERA_VV)*. This level is assigned to the different building zones and spaces that make up the RAS. Based on the most representative areas of the complex, a total of 27 different zones were considered (Figure 8). The Courtyard of the Maidens is identified as '_SERA_16'. This level of detail provides basic information on the primary elements of each area (according to the terminological standardization) that characterize the case study, without entering into a detailed study.
- *ULA-2. Global architectural elements (WWx-y00-SERA_VV)*. At this level, the architectural components are considered as a whole, and their boundaries are strictly determined by the architectural typology and orientation of the space. The Courtyard is made up of four galleries with opposing orientations (southeast, southwest, northwest and northeast). In this way, all components of the same type, orientation and constructive continuity are grouped together as a single spatial feature. Related to 'C.1. Conservation' block, this level provides data from the 'C.1.1. Basic information' section.
- *ULA-3. Specific architectural elements (WWx-y00-00-z_SERA_VV)*. The global architectural components are now segmented for a more detailed study. This division responds to three criteria: the presence of relevant elements that affect the continuity of the element (1); the detection of a clear compositional rhythm that allows the decomposition of the global element (2); and the agent's own criteria on applying the diagnosis protocol (3). Data from sections C.1.1., C.1.2., C.1.3. and C.1.4. is provided in this level. Thus, NDT data from the C.1.3. section is included in this ULA.

  Moreover, this level of detail includes the vertical component (-z), which enables an architectural element to be separated into different parts along its entire height. The implementation of this parameter is shown in Figure 8. It can be observed how three features are identified in the same spatial scope, one for each piece of plasterwork detected at different heights. The reference elevation is taken as the distance from the base of each piece to the initial floor elevation (0.0 m).

These considerations are included in the coding to identify each of the elements collected, including information related to the typological designation of the element and its associated area (Table 3). When the code values corresponding to the architectural characterization are null, the spatial feature corresponds to all the architectural elements, and thus the use of its associated spatial feature is intended for purely informative purposes Table 3.

Data modelling: 2D-GIS and 3D-GIS features

This section develops the workflow for integrating the technical information collected from the plasterwork in a 2D-GIS and 3D-GIS model.

Geometry model

The GIS model that has been developed is composed of both two-dimensional and three-dimensional

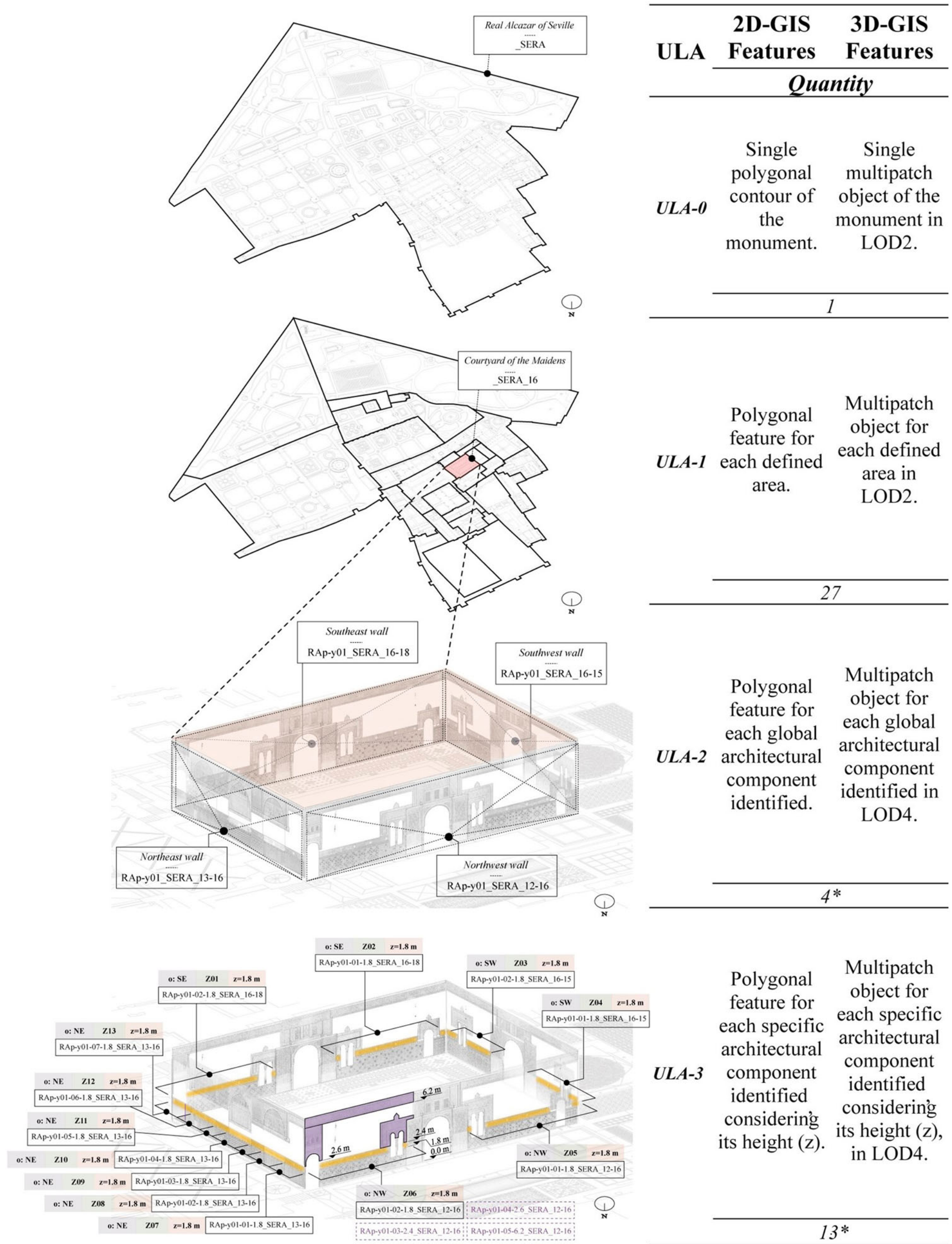


Figure 8. Spatial hierarchy for the designation of spaces and architectural elements. *Only counting plasterwork in the Courtyard.

Table 3. Identification code of the plasterwork according to architectural and spatial categorization.***

	Architectural definition			Spatial definition				
ULA	Primary element (WW)	Sub-element (x)	Component (y)	Global Id. (00)	Detail Id. (00)	Vertical Div. (z)	Case study Id. (SERA)	Zone (VV)
ULA-0	–	–	–	–	–	–	_SERA	–
ULA-1	–	–	–	–	–	–	_SERA	_16
ULA-2	RA	p	-y	01	–	–	_SERA	_16-18[a]
ULA-3	RA	p	-y	01	–01	–1.8	_SERA	_16-18[a]

[a]When the architectural elements defined are boundary elements or are located on a boundary element between two zones defined at ULA-1 level, the code assigned to their GIS feature reflects this.

features. The modelling of both is carried out differently, but they are linked and contain the same information.

The 2D features corresponding to each ULA have been drawn manually using the computer-aided design software AutoCAD Map 3D v.2021. These 2D

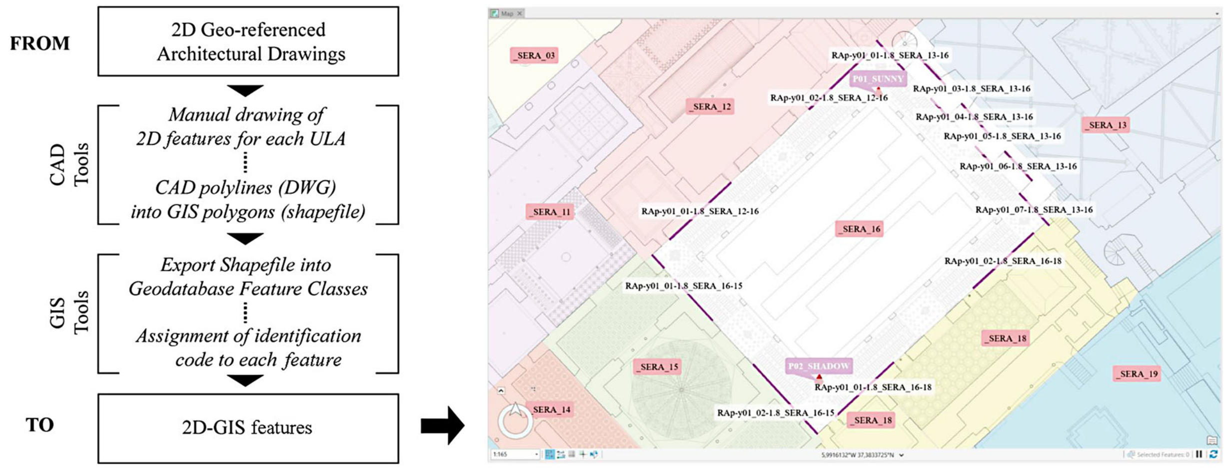


Figure 9. Workflow for the modelling of 2D-GIS features. In the figure, GIS features correspond to the areas of ULA-1 and the plasterwork studied of ULA-3.

polylines have been drawn on the geo-referenced base planimetry of the RAS previously created by the authors, thereby guaranteeing their correct geographical location. The WGS84 geographic projection system is used. These 2D features of each ULA were exported to shapefile files with polygonal geometry and imported into ArcGIS Pro v.2.9 software as independent layers. In order to facilitate their management, all 2D geometry layers are converted into feature classes of a single geodatabase. Finally, each feature is assigned its corresponding identification code (Figure 9). Figure 8 includes a quantification of the number of 2D features that have been modelled.

In the case of the 3D features, the modelling process is specific to each ULA (Figure 10). The features of ULA-0 and ULA-1 have been obtained through a semi-automatic modelling procedure following the methodology proposed by Hidalgo-Sánchez et al. (2022). This consists of using open data (in the form of files of clouds of points captured with LiDAR sensors from public Spanish institutions and 2D vectorial cadastral data) to obtain the LOD2[1] model of the RAS, which is enough to contain the information corresponding to these ULAs. On the other hand, the modelling of the ULA-2 and ULA-3 features focuses on the definition of the interior architectural elements of the monument and reaches LOD4, enabling a model capable of assimilating the NDT data relating to the plasterwork. The procedure followed for the modelling consists of the semi-automated extrusion and adoption of base heights of the drawn 2D-GIS features. Specific information fields controlling these parameters have been defined in the database as GEOM_HEIGHT_m, to control the extrusion height of each feature; and GEOM_BASELEV_m, to control its elevation height. The three-dimensional models obtained (both LOD2 and LOD4) present a 'Multipatch' geometry type. Further to the features identified, the GIS model includes 2D and 3D point features that correspond to the two environmental sensors used, named P01_SUNNY and P02_SHADOW.

Integration of diagnosis and monitoring data

Once the geometric modelling process has been completed, the information from the NDTs carried out is linked to the graphic features of the plasterwork under study (ULA3-LOD4). Each type of NDT generates different types of results (alphanumeric, images, graphics, etc.), in addition to the general information of each test (authorship, date, description, etc.).

In order to facilitate the initial integration of NDT data into the GIS model, forms have been created (Figure 12) linked to a supporting database developed in Microsoft Excel v.2021 software, including the thematic fields defined. The input of the NDT results into the database has been automated via macros implemented in the form. The form enables not only the selection of a specific GIS feature, but also the creation of as many groups of NDT fields as necessary. In order to prevent duplications, when entering new data from the form, the macro generates a field with a random alphanumeric code, unique for each set of fields related to a given NDT.

When the technicians fill in the information, the administrator of the GIS model links the database to the 2D and 3D features of the modelled plasterwork, which constitutes its initial attribute table. The linking is done by means of the geo-processing tool 'Join', by taking the so-called ID as a common field: this

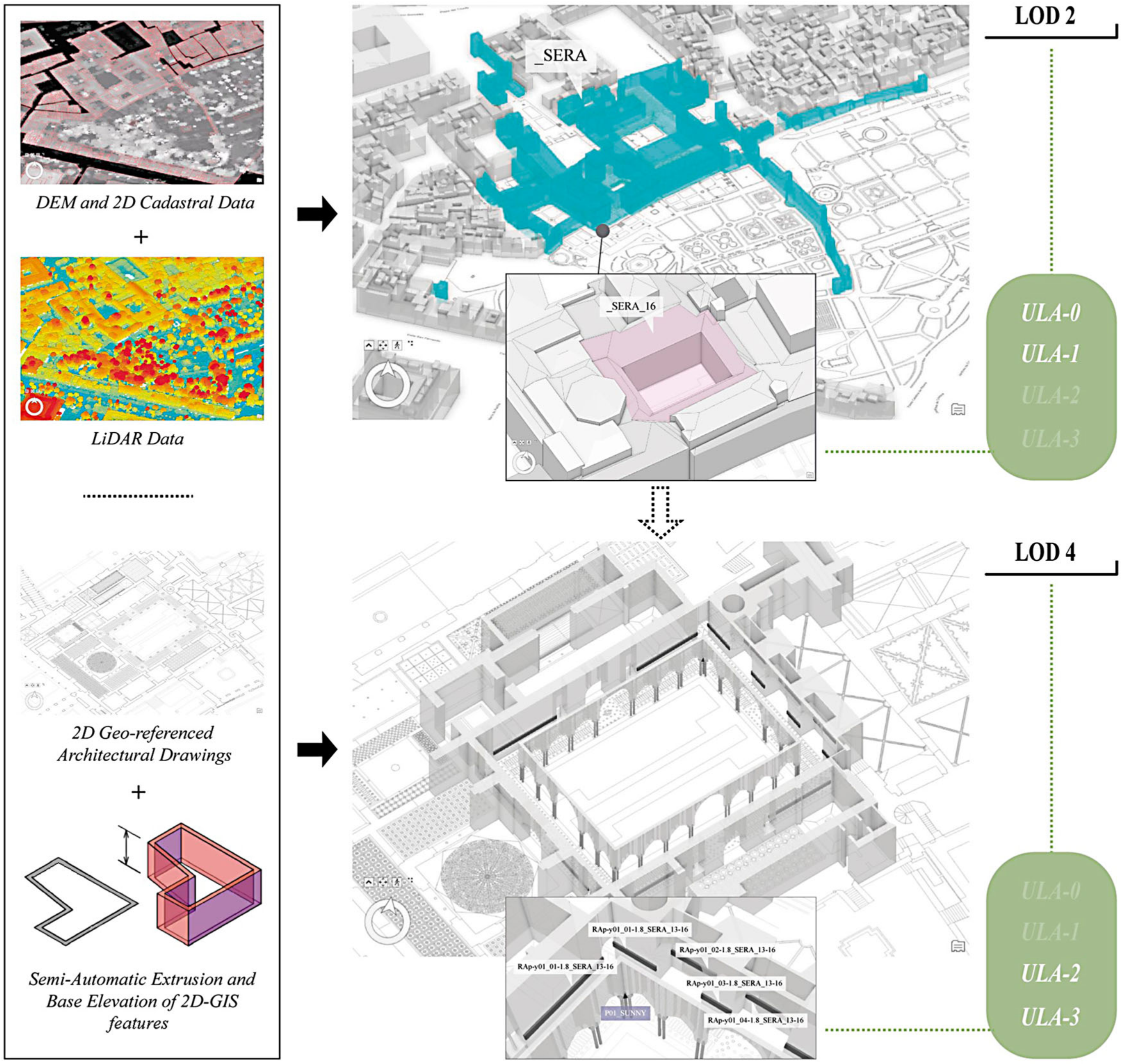


Figure 10. Workflow for the modelling of 3D-GIS features. In the figure, GIS features corresponding to the whole monument (ULA-0), different areas (ULA-1) and the plasterwork under study (ULA-3).

includes the unit code defined for each feature (see Table 3). The introduction of NDT data can be performed directly in a manual way in the attribute table of the GIS model. This procedure is applicable to all other ULAs (Figure 11).

A similar process is followed for the integration of the data collected by the two environmental sensors. These measurements are included in a CSV data table that is entered into the GIS model as linked information, to be subsequently processed and charted. These charts are entered into the attribute table of the sensor.

Unlike alphanumeric information, images (PNG, JPG, and TIFF), 3D objects (OBJ), text documents (TXT and PDF) and supplementary data tables (XLS and CSV) corresponding to each NDT are included as attachments in the attribute tables of the GIS features. For this purpose, they have been hosted in digital repositories of the University of Seville, with web links that allow not only their display in HTML pop-up windows linked to the GIS features, but also their direct download from the model itself.

Output data: GIS Cloud database publication and updating

The GIS model with semantic information and defined data structure is published online, hosted on the cloud-based platform ArcGIS Online. The procedure firstly consists of publishing the generated 2D and 3D features that make up the local GIS model as feature and scene layers hosted on the platform. Once published, a map and a web scene are generated using the portal tools, in which the published layers are included. Finally, a web application has been created that includes both as linked views. This web application is shared with the users and technicians, whereby the administrators of

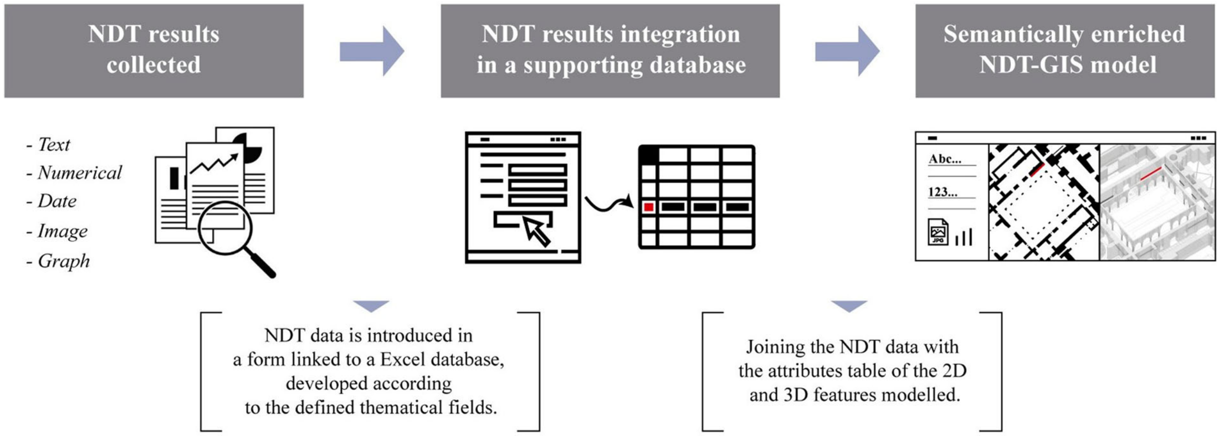


Figure 11. Workflow for the initial integration of NDT data into the GIS model.

this information can establish privacy ranges for each specific content and type of user. It should be reiterated that the local GIS model must have the Web Mercator as the coordinate system on ellipsoid WGS84, which is the default system of the ArcGIS Online platform, thus avoiding compatibility problems.

Regarding the update process, this can be carried out in two different ways: from the local GIS model or from the GIS Cloud model. In the first case, the administrator of the GIS model is the only person with the capacity to update and modify the model. The local GIS model with the new data overwrites the GIS model hosted on the Cloud platform. In the second case, the technicians and users authorized to edit the attributes of the model can include and modify the information directly in the GIS Cloud environment. These changes must be accepted by the GIS model administrator to become effective. In either case, no overlapping or loss of information occurs since any modification of the online model is registered on the platform.

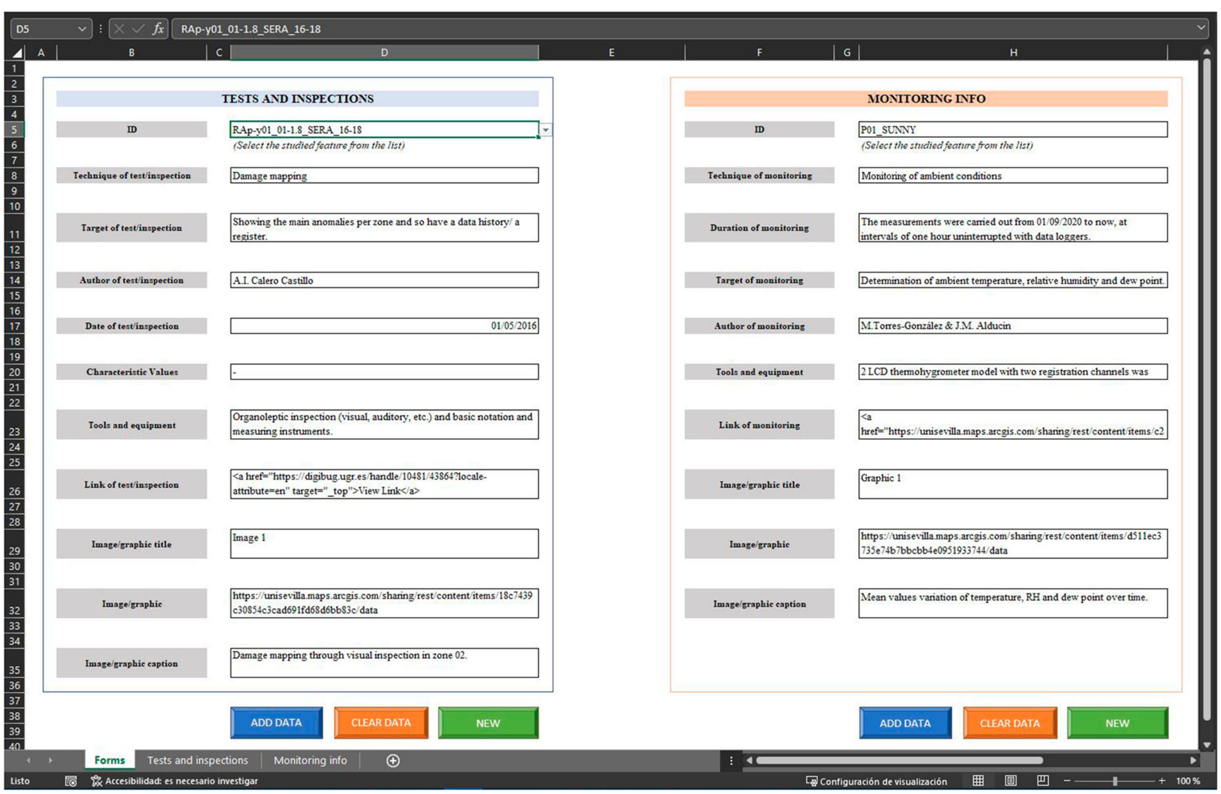


Figure 12. Forms created to fill in the Excel database.

Discussion and results

The main results derived from the application of the proposed methodology are shown below. These results, referred to the plasterwork, can be replicated in the rest of the architectural elements of the RAS, according to the established standardization.

Centralized management

Data from NDTs carried out is introduced into the GIS model in accordance with the established methodological criteria. A total of 47 NDTs have been included to date, with 456 fields of information filled in regarding all the pieces of plasterwork and environmental sensors of the ULA3. The database also includes 67 downloadable attachments in 9 different file formats. The data collected, in turn, comes from work carried out independently by seven technicians. Their inclusion has been performed progressively, both from the local GIS model and from the GIS Cloud model. This demonstrates the large amount of information that can be centrally managed through the proposed NDT-GIS workflow, and the adaptability of the database implemented.

NDT data contained in the modelled LOD4 GIS features is shown in detail in Table S6 (Online supplementary material). The plasterwork in the northeast gallery, currently in the worst state of conservation, provides the most information to the database.

Each of the spatial features modelled (both 2D and 3D) has an associated pop-up window in the form of a particular technical sheet, which includes the results of the NDT, thereby enabling the information on the database to be consulted from the model itself. These technical sheets are organized in terms of the fields defined in Table 2 and are linked to the attribute table of the GIS features so that they automatically reflect any update of the database. These sheets also provide access to the attached documentary information without needing to download it. Its purpose is to facilitate the comprehensive and operational management of NDT data.

Figure 13 represents the generic graphical interface displayed when consulting the LOD4 GIS model information. From the 2D and 3D views, it is possible to access the technical data sheets linked to the GIS features, with their corresponding NDT data. This is exemplified for the case of plasterwork (in red) and one of the environmental sensors (in blue).

Diagnosis display

This section proves the analytical capabilities underlying the creation of a spatial data model in a GIS environment, by focusing on the data collected on the plasterwork.

Spatial queries

Alphanumeric data included in the spatial database allows statistical categories to be established for their graphic comparison of the plasterwork studied. Further to the visual information, statistics are not only obtained on the minimum, maximum and mean values of the data collected, but also on the standard deviation value. This makes it possible to identify which friezes are within the established reference values. Likewise, the GIS model complements the interpretation of the results of the NDTs, including information about their orientation, location and relationship with other elements.

Figure 14 shows a visual analysis of the plasterwork based on its mechanical properties, both in 2D and 3D. Specifically, Figure 14(a) shows a comparison of the C-Shore Hardness values obtained, where intervals that set values above 45 have been established as the admissible threshold. On the other hand, Figure 14(b) shows the surface humidity values measured in each piece of the plasterwork, whereby values above 80% are established as the critical value. This analysis reveals that the plasterwork located in the northeast gallery of the Courtyard is in the worst state of conservation, since it has the poorest values in the mechanical property tests. The rest of the plasterwork has admissible results according to the reference values.

The low mechanical capacity of this plasterwork leads to a lack of adhesion to the wall, resulting in the detachment of material, cracks and the appearance of voids, as confirmed by the information included in the database. Likewise, thanks to the GIS model, a hypothesis can be established to justify these values. The wall where this plasterwork is located, unlike the rest, does not back onto other rooms (with air flow moving behind them), but is in direct contact with the soil and the foundations of the Gothic Palace (_SERA_13), located at a higher level than the Courtyard (_SERA_16). Therefore, this wall is more severely affected by the soil humidity. This circumstance is verified by consulting the temperature values recorded in the thermographs taken, which are also included in the database. The results of all the tests carried out have been useful in establishing this hypothesis, thereby validating the convenience of the centralized management proposed and the operational capability of the GIS model.

Processing monitoring info

Data collected by the two environmental sensors located at the north (P01_SUNNY) and south (P02_SHADOW) corners of the Courtyard has been employed to produce

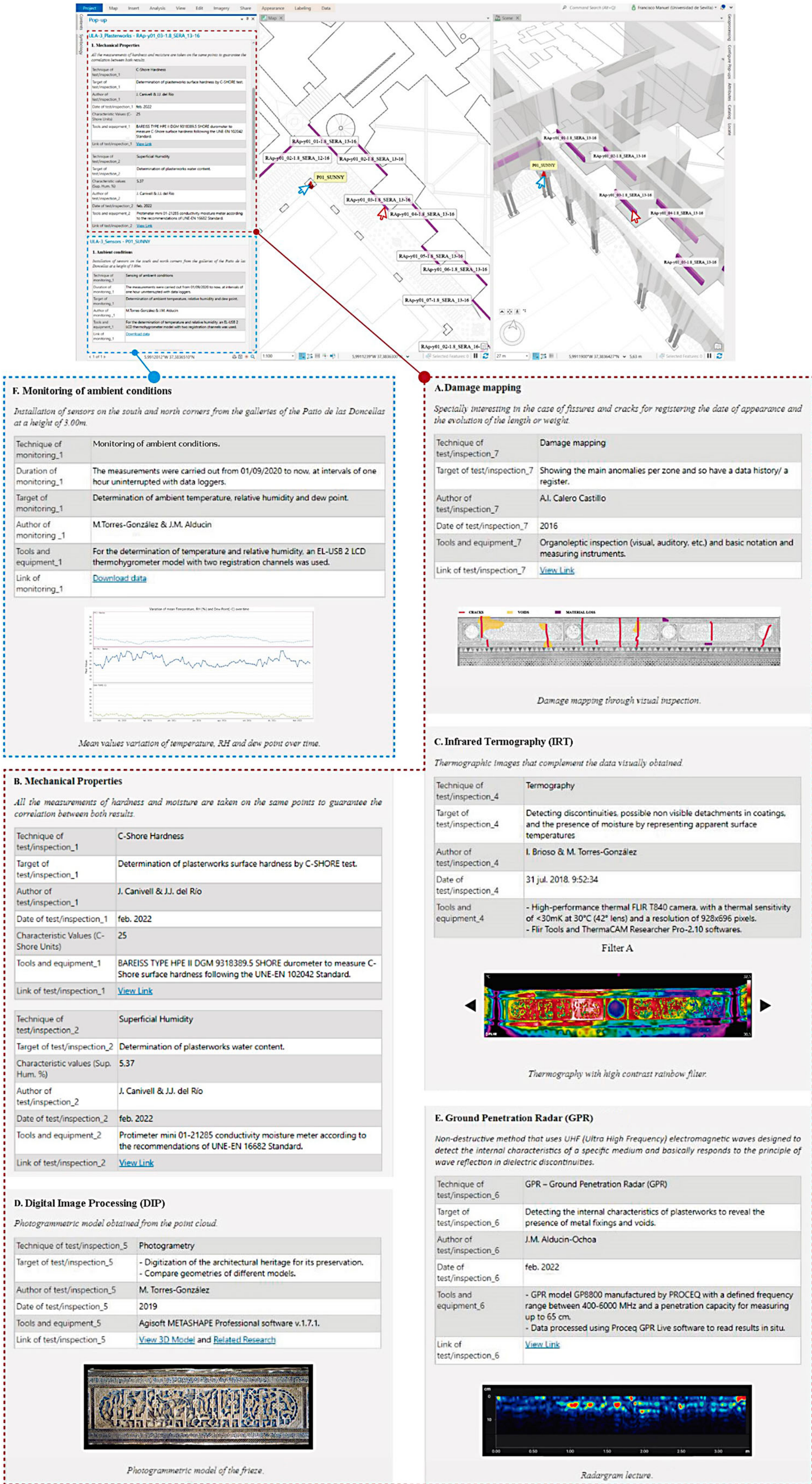
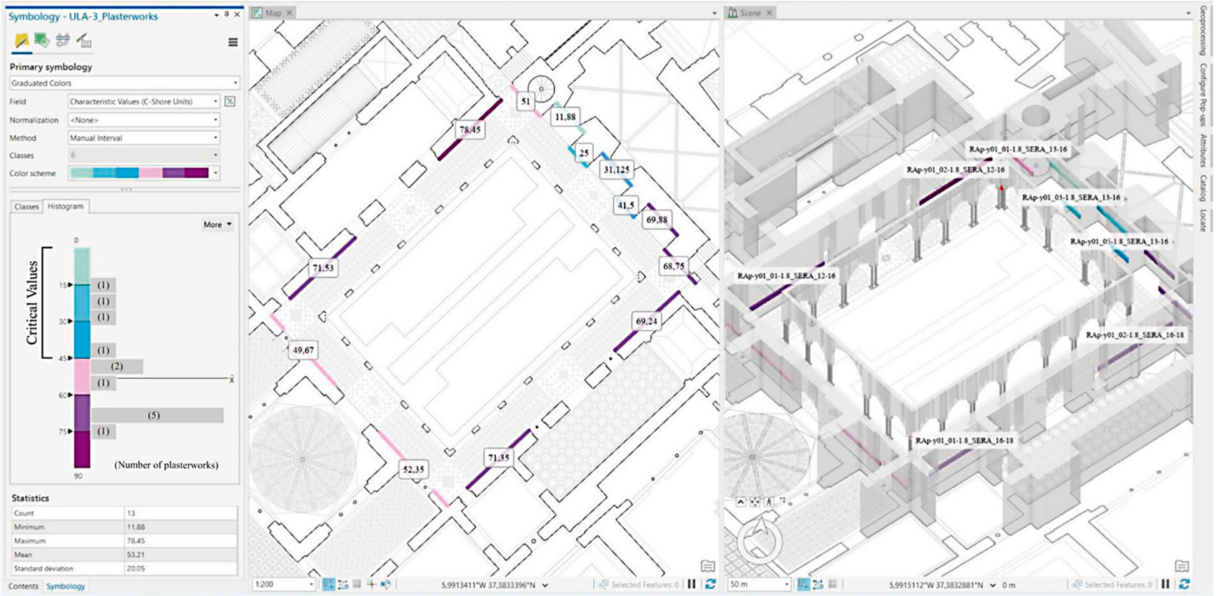
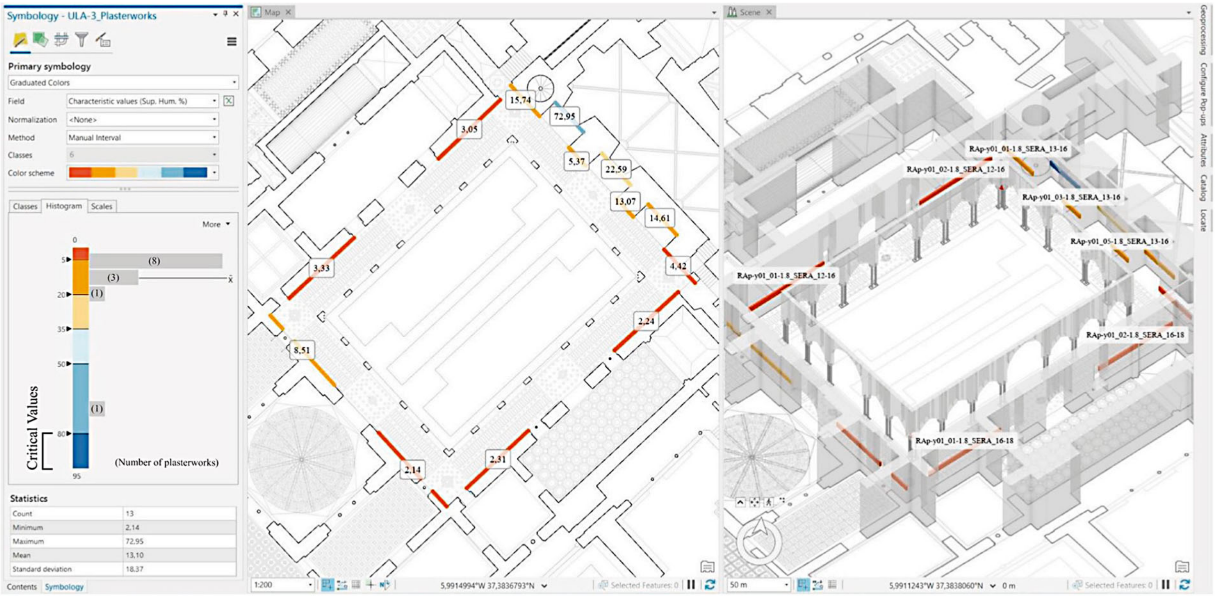


Figure 13. Technical sheets integrated into the GIS model database.



(a)



(b)

Figure 14. Spatial queries of mechanical properties: (a) C-Shore Hardness and (b) Superficial Humidity.

specific charts that enable relations between the measured parameters to be established. To this end, this data (in CSV format) has been introduced into the GIS model as a data table. Additionally, the charts are exported and included as part of the technical datasheet information linked to the '3D Point' features representing the sensors in the GIS model (see Figure 13). The Relative Humidity (RH) parameter shows the largest oscillations between the two measurement points (Figure 15). RH values above 65% are considered dangerous, and those above 95% are considered critical. The distribution charts show an annual average RH value of 59.45% for the sunny points and 63.63% for the shaded points. However, there is a high percentage of hours exceeding the recommended 65% RH and, specifically, in the shaded area, 95% RH is exceeded in certain periods.

This data may exert considerable influence on the state of conservation of the plasterwork, in addition to the factors mentioned above. Nevertheless, to establish an accurate correlation, in-depth analyses must be carried out, which falls outside the scope of this research. However, this first interpretation derived from the GIS model is useful as a guide to these more specific studies.

Figure 15. Line and distribution charts created based on monitoring info from sensors located on sunny and shadow points of the Courtyard.

Geographic web services

In keeping with the objectives of this research, these results obtained should be shared online to facilitate their access and management by the agents involved in the preventive conservation process. The contents published, depending on their nature and state of development, can be considered as either open or closed data. The geographic web services provided are derived from the set of attribute services generated. These information layers are used as content in web services of editable and searchable 2D maps and 3D scenes, which are integrated into the web application.

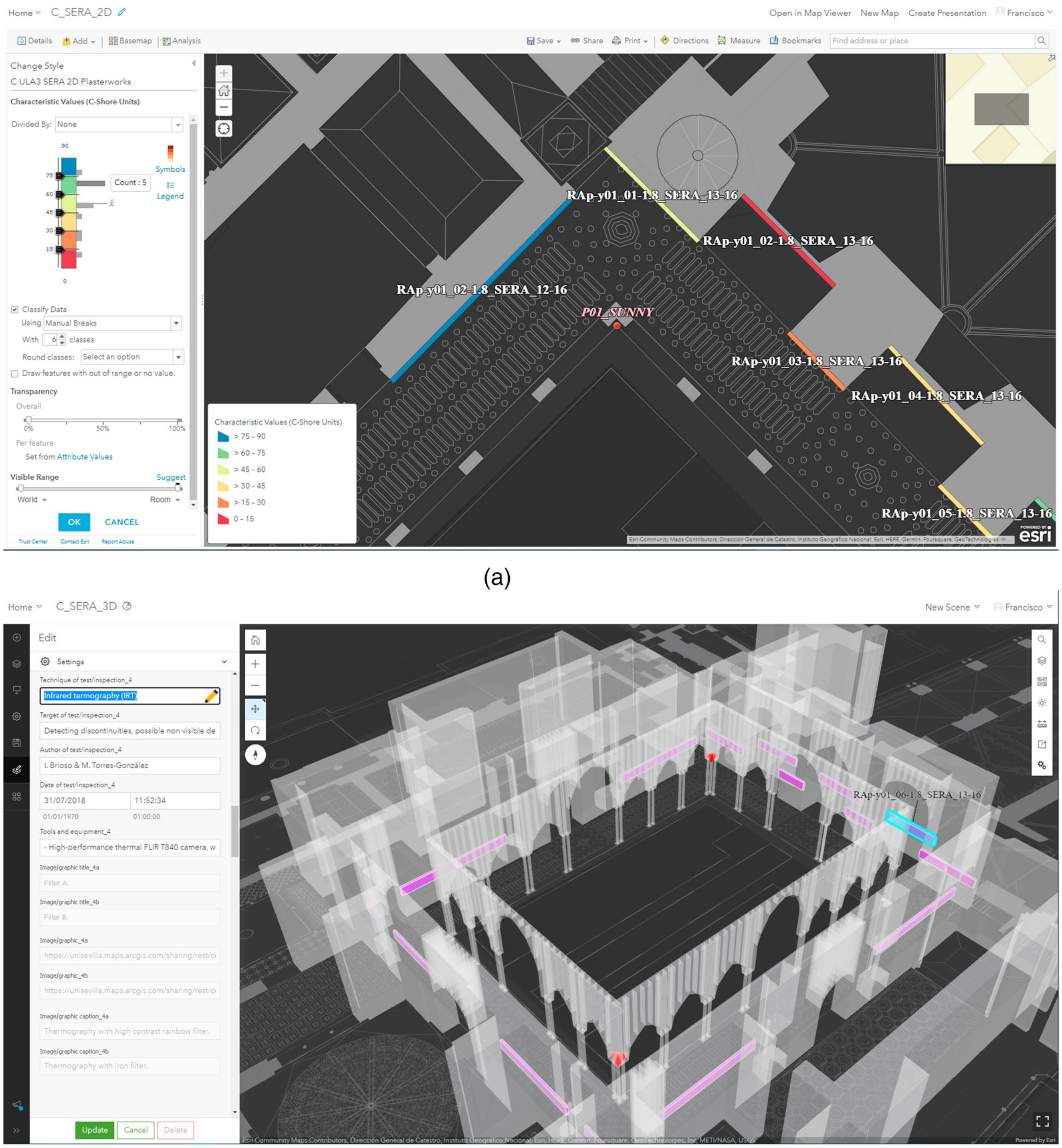
These services have been developed particularly for the thematic information category '(C) Diagnosis'. Each category has its own geographic web services, accessible from the same GIS Cloud portal. This enables specialists in one area to work with detailed information, with the possibility of consulting information from other categories. It also facilitates the process of selecting the geographic services shared as open GIS data, without compromising those reserved for internal use.

Attribute web services

The attribute services or layers are those that make up the web content derived from this research. They include the GIS features defined for each ULA and their associated data. This data is published in ArcGIS Online as hosted layers with 2D vector geometry (Feature layer) and Multipatch 3D geometry (Scene Layer). Furthermore, attribute services have also been published including the base geometry of the model (in *italics* in Table 4), providing architectural context

Table 4. Geographic services published online.

ULA	Attribute web services (Layers)	Number of GIS features	Web maps and web scenes	Web Map Application (WMA)
ULA0	C_ULA0_SERA_2D	1	C_SERA_2D	C_Diagnosis_SERA
	C_ULA0_SERA_LOD2_3D		C_SERA_3D	
ULA1	C_ULA1_SERA_2D	27	C_SERA_2D	
	C_ULA1_SERA_LOD2_3D		C_SERA_3D	
ULA2	C_ULA2_SERA_2D_Plasterwork	4	C_SERA_2D	
	C_ULA2_SERA_LOD4_3D_Plasterwork		C_SERA_3D	
ULA3	C_ULA3_SERA_2D_Plasterwork	13	C_SERA_2D	
	C_ULA3_SERA_3D_Plasterwork		C_SERA_3D	
	C_ULA3_SERA_2D_Sensors	2	C_SERA_2D	
	C_ULA3_SERA_3D_Sensors		C_SERA_3D	
ULA2 and ULA3	*BASE_BLUEPRINT_2D*	–	*C_SERA_2D and C_SERA_3D*	
	BASE_MODEL_LOD4_3D	–	*C_SERA_3D*	
Total	12	47	2	1



(a)

(b)

Figure 16. Spatial query on the web map (a). Entry of NDT data via the web scene (b).

to the rest of the GIS features. All the layers have the same geographic projection system: WGS84.

Web maps and web scenes

It has been demonstrated that the transversal nature of the proposed database allows the development of thematic cartographies based on spatial queries with different needs. These mappings can be replicated using the information hosted on the cloud-based platform. This in turn enables the various agents not only to interactively illustrate the elements and attributes of the database, but also to share analyses, thereby reaching a degree of detail unusual for this type of platform. For the case of this research, two web cartographies have been created, a 2D web map (C_SERA_2D) and a 3D web scene (C_SERA_3D), corresponding to the local GIS model (Figure 16).

Figure 16(a) illustrates the possibility of performing the same spatial analyses as those carried out in the local GIS model on the plasterwork. Figure 16(b)

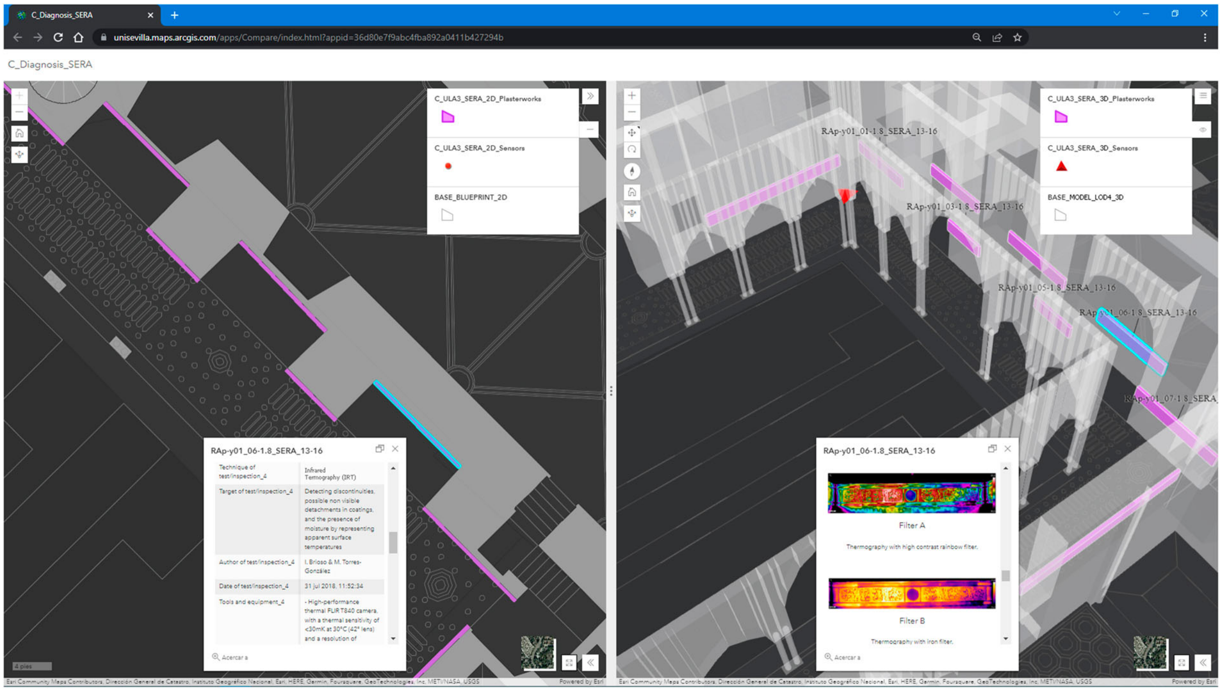


Figure 17. Consultation of NDT data associated with the GIS feature of one of the pieces of plasterwork using the web application (WMA).

shows the inclusion of NDT data, in the form of thermographic images, in the attribute table of one of the pieces of plasterwork from the web scene.

Web mapping application

Finally, a web mapping application (WMA) has been developed within the ArcGIS Online platform. For this, the tool 'ArcGIS Configurable Apps' from ESRI has been employed. The procedure initially consisted of choosing the available pre-configured template that best suited the content and intended purpose. Then, the template has been customized by adding complementary functionalities (e.g. section box, synchronization of views and pop-up windows, measurement tools, basemaps options, etc.).

The purpose of this WMA is eminently for visualization and interactive consultation of model information. Unlike the map and scene above, it is not possible to edit the attribute services or perform spatial analysis directly in the WMA. However, any changes made to the map and the web scene within it are automatically reflected in the WMA. As an example of this workflow, Figure 17 shows the NDT data entered in the previous subsection, already updated in the WMA. In this respect, both services are complementary. Maps and web scenes are useful tools for technicians who carry out tests and fill in information. On the other hand, WMAs are more useful for quick consultation of information and dissemination of results.

Conclusions

The research has been focused on the study of plasterwork located in the Courtyard of the Maidens of the RAS. Several NDTs have been carried out on these specific components and their results have been introduced on the GIS model built while following the fundamentals of the spatial database proposed.

The implementation of this database proves that it is a flexible methodology capable to adapt to new scenarios, whose basic principles can be replicated in different types of case studies and specific components and materials. Its thematic content structure, developed for diagnosis data in this paper, enables the inclusion of results from any type of NDT method, since it is extensive to both SDT and DT methods. This, together with its availability as online content hosted on a GIS Cloud platform, provides easy access and updating of the information, and promotes collaboration between technicians from different areas. Likewise, by including specific fields that consider the temporal variable, comparisons can be made of the results of the various tests carried out by different and independent technicians over a given chronological period.

GIS tools provide the capacity to make preliminary diagnoses in an agile manner with the data collected, which is highly useful as a basis for later studies of a more detailed nature. These initial diagnoses also help to prioritize restoration and maintenance interventions by the comparative analysis of the data corresponding to each ULA, facilitating decision-making and the establishment of action guidelines. These characteristics, reinforced by their multi-scale and interdisciplinary nature, render the spatial database proposed as an optimal digital tool for predictive maintenance, preventive conservation and dissemination of architectural values.

Finally, the difficulties encountered in relation to the 3D geometric modelling of GIS features deserve mention, especially those with complex geometry. Although semi-automatic modelling procedures have been applied to optimize the process, the modelling capabilities of current GIS tools remain limited at the architectural scale, in comparison with other CAD or BIM tools.

As future work, it would be possible to evaluate the aforementioned replicability of this protocol in different heritage contexts, to evolve its systematics according to the results obtained. In this regard, it is considered that its integration in current preventive conservation plans can complement their existing tools, by providing a field of experimentation for the methodology. Moreover, in terms of analytical and information management possibilities, interesting lines of research are opened related to the temporal dimension (4D). A prime example is given by the real-time monitoring of technical parameters linked to the GIS model, which would enable a completely updated follow-up of the conditions of the study elements, as well as providing a greater volume of data. In this way, the results of different NDTs could be more accurately correlated carrying out spatial and statistical analyses by using Big Data or Artificial Intelligence tools.

To conclude, the extensive creation of different geographic services allows the development of open GIS-based tools with different purposes. Collaborating with local SDIs for the inclusion in its public repositories could generate an interesting feedback process. Moreover, this strategy aligns the fundamentals of UN 2030 SDGs, in terms of digitization for the promotion of smart and sustainable cities.

Note

1. Five levels of detail (LOD) are distinguished by the CityGML standard (Gröger & Plümer, 2012) for the representation of buildings in GIS environment, from LOD0 to LOD4. According to this, LOD2 present buildings as prisms in which the geometry of their roofs has been defined, whereas LOD4, the highest, includes the indoor elements of the building for its complete definition.

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Disclosure statement

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Geolocation information

The geographical coordinates are: 37.362511829239324 (Latitude), -5.986857053806982 (Longitude).

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References

Acierno, M., Cursi, S., Simeone, D., & Fiorani, D. (2017). Architectural heritage knowledge modelling: An ontology-based framework for conservation process. *Journal of Cultural Heritage*, *24*, 124–133. https://doi.org/10.1016/j.culher.2016.09.010

Adamopoulos, E., Volinia, M., Girotto, M., & Rinaudo, F. (2020). Three-dimensional thermal mapping from IRT images for rapid architectural heritage NDT. *Buildings*, *10* (10), 187–118. https://doi.org/10.3390/buildings10100187

AENOR. (2014). *UNE-EN 102042. Gypsum plasters. Other test methods.* Asociación Española de Normalización y Certificación, AENOR.

AENOR. (2018). *UNE-EN 16682. Conservation of cultural heritage – Methods of measurement of moisture content, or water content, in materials constituting immovable cultural heritage.* Asociación Española de Normalización y Certificación, AENOR.

Agapiou, A., Lysandrou, V., Alexakis, D. D., Themistocleous, K., Cuca, B., Argyriou, A., Sarris, A., & Hadjimitsis, D. G. (2015). Cultural heritage management and monitoring using remote sensing data and GIS: The case study of Paphos area, Cyprus. *Computers, Environment and Urban Systems*, *54*, 230–239. https://doi.org/10.1016/j.compenvurbsys.2015.09.003

Alejandre Sánchez, F. J., Blasco López, F. J., Flores Alés, V., Villegas-Sánchez, R., & Freire, M. T. (2021). Study of the influence of limewash on the conservation of Islamic plasterworks through weathering tests. *International Journal of Architectural Heritage*, *15*(4), 580–592. https://doi.org/10.1080/15583058.2019.1632393

Almagro Gorbea, A. (2005). La recuperación del jardín medieval del Patio de las Doncellas [The recovery of the medieval garden in the Courtyard of the maidens]. *Apuntes Del Alcázar de Sevilla*, *6*, https://www.alcazarsevilla.org/wp-content/pdfs/APUNTES/apuntes6/restauracion2/contenidos_res2.html

Almagro Gorbea, A. (2007). El Alcázar de Sevilla. Un palacio musulmán para un rey cristiano [The Alcazar of Seville. A Muslim palace for a Christian king]. Cristianos y Musulmanes En La Península Ibérica: La Guerra, La Frontera y La Convivencia. XI Congreso de Estudios Medievales (pp. 331–365).

Ávila Rodríguez, M. (2019). *Aplicación de la tecnología 3D a las técnicas de documentación, conservación y restauración de Bienes Culturales* [Application of 3D technology to the Techniques of Documentation, Conservation and Restoration of Cultural Assets] [Doctoral dissertation]. Universidad Complutense de Madrid. Facultad de Bellas Artes.

Battini, C., & Vecchiattini, R. (2018). Data parametric representation for monitoring of cultural heritage. *Applied Geomatics*, *10*(3), 191–204. https://doi.org/10.1007/s12518-018-0219-1

Biscarini, C., Catapano, I., Cavalagli, N., Ludeno, G., Pepe, F. A., & Ubertini, F. (2020). UAV photogrammetry, infrared thermography and GPR for enhancing structural and material degradation evaluation of the Roman masonry bridge of Ponte Lucano in Italy. *NDT & E International*, *115*, 1–15. https://doi.org/10.1016/j.ndteint.2020.102287

Blasco López, F. J., & Alejandre Sánchez, F. J. (2013). Porosity and surface hardness as indicators of the state of conservation of Mudéjar plasterwork in the Real Alcázar in Seville. *Journal of Cultural Heritage*, *14*(2), 169–173. https://doi.org/10.1016/j.culher.2012.04.010

Cabrera-revuelta, E., & Aguilar-camacho, J. (2022). Influence of the camera lens in the photogrammetric survey of historic plasterworks. Comparative study in the royal alcazar of Seville. In Ródenas-López, M.A., Calvo-López, J., Salcedo-Galera, M. (eds.), *Architectural graphics* (pp. 1–10). Springer. https://doi.org/10.1007/978-3-031-04632-2_19

Calero-Castillo, A. I., García Bueno, A., López Cruz, O., & Medina Flórez, V. J. (2016). Las yeserías del Patio de las Doncellas del RAS. Avance de resultados de la caracterización de materiales y la técnica. [The Plasterwork at the Courtyard of the Maidens in the RAS. Advance of results of the characterization of materials and technique]. *Al-Qanṭara*, *37*(1), 129–141. https://doi.org/10.3989/alqantara.2016.006

Campanaro, D. M., Landeschi, G., Dell'unto, N., & Touati, A.-M. L. (2016). 3D GIS for cultural heritage restoration: A 'white box' workflow. *Journal of Cultural Heritage*, *18*, 321–332. https://doi.org/10.1016/j.culher.2015.09.006

Campiani, A., Lingle, A., & Lercari, N. (2019). Spatial analysis and heritage conservation: Leveraging 3-D data and GIS for monitoring earthen architecture. *Journal of Cultural Heritage*, *39*, 166–176. https://doi.org/10.1016/j.culher.2019.02.011

Campos de Alvear, R. (2020a). Programa de actuaciones para la conservación-restauración de las yeserías del Palacio Mudéjar [Programe of actions for the conservation-restoration of the plasterwork of the mudéjar palace]. *Apuntes Del Alcázar de Sevilla*, *20*, 63–85.

Campos de Alvear, R. (2020b). Programme of actions for the conservation-restoration of the plasterwork of the Mudéjar Palace. *Apuntes Del Alcázar de Sevilla*, *20*, 63–85.

Canciani, M., Ceniccola, V., Messi, M., Saccone, M., & Zampilli, M. (2013). A 3D GIS method applied To cataloging and restoring: The case of aurelian walls At Rome. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-5/W2*, 143–148. https://doi.org/10.5194/isprsarchives-XL-5-W2-143-2013

Chenaux, A., Murphy, M., Pavia, S., Fai, S., Molnar, T., Cahill, J., Lenihan, S., & Corns, A. (2019). A review of 3D GIS for use in creating virtual historic Dublin. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIIXLII-2/W9*, 249–254. https://doi.org/10.5194/isprs-archives-XLII-2-W9-249-2019

Coba Peña, A. C., Calero Castillo, A. I., Collado Montero, F. J., Hernández Pablos, A., & Medina Flórez, V. J. (2016). Reconstrucción virtual de color sobre la policromía del alfarje y yeserías del patio de las Doncellas [Virtual color reconstruction on the polychrome of the paneled ceiling and plasterwork of the Maidens courtyard]. *PH Investigación: Revista Del IAPH Para La Investigación Del Patrimonio Cultural*, *7*, 1–24.

Colucci, E., De Ruvo, V., Lingua, A., Matrone, F., & Rizzo, G. (2020). HBIM-GIS integration: From IFC to CityGML standard for damaged cultural heritage in a multiscale 3D GIS. *Applied Sciences*, *10*(4), 1356. https://doi.org/10.3390/app10041356

Costanzo, A., Minasi, M., Casula, G., Musacchio, M., & Buongiorno, M. F. (2015). Combined use of terrestrial laser scanning and IR thermography applied to a historical building. *Sensors*, *15*(1), 194–213. https://doi.org/10.3390/s150100194

Diz-Mellado, E., Mascort-Albea, E. J., Romero-Hernández, R., Galán-Marín, C., Rivera-Gómez, C., Ruiz-Jaramillo, J., & Jaramillo-Morilla, A. (2021). Non-destructive testing and finite element method integrated procedure for heritage diagnosis: The Seville Cathedral case study. *Journal of*

Building Engineering, *37*, Article 102134. https://doi.org/10.1016/j.jobe.2020.102134

European Commission. (2019). *Cooperation on advancing digitisation of cultural heritage*. https://www.vi-mm.eu/wp-content/uploads/2016/12/scannedsignedDeclaration090419pdf.pdf

European Commission. (2021). *Commission recommendation (EU) 2021/1970 of 10 November 2021 on a common European data space for cultural heritage*.

Ferreira-Lopes, P. (2018). Achieving the state of research pertaining to GIS applications for cultural heritage by a systematic literature review. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-4*, https://doi.org/10.5194/isprs-archives-XLII-4-169-2018

Freyer, D., & Voigt, W. (2003). Crystallization and phase stability of CaSO 4 and CaSO 4-based salts. *Monatshefte fur Chemie/Chemical Monthly*, *134*(5), 693–719. https://doi.org/10.1007/s00706-003-0590-3

Galantucci, R. A., & Fatiguso, F. (2019). Advanced damage detection techniques in historical buildings using digital photogrammetry and 3D surface analysis. *Journal of Cultural Heritage*, *36*, 51–62. https://doi.org/10.1016/j.culher.2018.09.014

García, J. (2020). Preventive conservation plan for the Royal Alcázar of Seville. *Apuntes Del Alcázar de Sevilla*, *20*, 171–193.

Gorbea, A. A. (2003). Planimetría del Alcázar de Sevilla. *Loggia, Arquitectura & Restauración*, *156–15*, 156–161. https://doi.org/10.4995/loggia.2003.3563

Grinzato, E. (2012). IR thermography applied to the cultural heritage conservation. 18th world conference on nondestructive testing, 2–5.

Gröger, G., & Plümer, L. (2012). CityGML – Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, *71*, 12–33. https://doi.org/10.1016/j.isprsjprs.2012.04.004

Günay, S. (2012). Spatial information system for conservation of historic buildings case study: Doğanlar church İzmir. 23RD CIPA congress.

Hidalgo-Sánchez, F. M., Mascort-Albea, E. J., Kada, M., Romero-Hernández, R., Canivell, J., & López-Larrínaga, F. (2022). 3D GIS semi-automatized modelling procedure for the conservation of the PHiM: Heritage municipal buildings of Seville (Spain). A New dimension for urban cultural data management. *Journal on Computing and Cultural Heritage*, *15*(1), 1–25. https://doi.org/10.1145/3467976

Iandelli, N., Coli, M., Donigaglia, T., & Ciuffreda, A. L. (2021). An unconventional field mapping application: A complete opensource workflow solution applied to lithological mapping of the coatings of cultural heritage. *ISPRS International Journal of Geo-Information 2021*, *10*(6), 357. https://doi.org/10.3390/ijgi10060357

Ivan Apollonio, F., Basilissi, V., Callieri, M., Dellepiane, M., Gaiani, M., Ponchio, F., Rizzo, F., Raffaele Rubino, A., Scopigno, R., & Sobra, G. (2018). A 3D-centered information system for the documentation of a complex restoration intervention. *Journal of Cultural Heritage*, *29*, 89–99. https://doi.org/10.1016/j.culher.2017.07.010

Junta de Andalucía. (1998). Tesauro de patrimonio histórico Andaluz [Thesaurus of the Andalusian Historical Heritage]. Instituto Andaluz del Patrimonio Histórico. https://guiadigital.iaph.es/tesauro-patrimonio-historico-andalucia

Kilic, G. (2015). Using advanced NDT for historic buildings: Towards an integrated multidisciplinary health assessment strategy. *Journal of Cultural Heritage*, *16*(4), 526–535. https://doi.org/10.1016/j.culher.2014.09.010

Kukela, A., & Seglins, V. (2013). Non-destructive methods for evaluation of the state of preservation in historical stone monuments: The case study of the step Pyramid in Saqqara. *Studia Quaternaria*, *30*(2), 109–114. https://doi.org/10.2478/squa-2013-0011

Kutasi, D., & Vidovszky, I. (2010). The cost effectiveness of continuous maintenance for monuments and historic buildings. *Periodica Polytechnica Architecture*, *41*(2), 57. https://doi.org/10.3311/pp.ar.2010-2.03

Lobovikov-Katz, A., Martins, J., Ioannides, M., Sojref, D., & Degrigny, C. (2018). Interdisciplinarity of cultural heritage conservation making and makers: Through diversity towards compatibility of approaches. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11196 LNCS, 623–638. https://doi.org/10.1007/978-3-030-01762-0_55/FIGURES/5

López González, L. (2015). *Aplicación de herramientas GIS para la cartografía y correlación de datos de ensayos no destructivos en el diagnóstico de edificios históricos* [Application of GIS for mapping and data correlation from NDT in the diagnosis of heritage buildings] [Doctoral dissertation]. Polytechnic University of Madrid. https://doi.org/10.20868/UPM.THESIS.39800

Merello, P., Pérez, M. C., Pérez-Miralles, J., García-Diego, F. J., Fernández-Navajas, A., & Zarzo, M. (2013). Basic descriptive statistical methods for monitoring and evaluation of microclimates in cultural heritage. In Rogerio-Candelera, M.A., Lazzari, M., & Cano, E. (eds.), *Science and technology for the conservation of cultural heritage* (1st ed., pp. 23–26). CRC Press. https://doi.org/10.1201/B15577-6

Messaoudi, T., Véron, P., Halin, G., & De Luca, L. (2018). An ontological model for the reality-based 3D annotation of heritage building conservation state. *Journal of Cultural Heritage*, *29*, 100–112. https://doi.org/10.1016/j.culher.2017.05.017

Moropoulou, A., Avdelidis, N. P., Karoglou, M., Delegou, E. T., Alexakis, E., & Keramidas, V. (2018). Multispectral applications of infrared thermography in the diagnosis and protection of built cultural heritage. *Applied Sciences*, *8*(3), 284. https://doi.org/10.3390/app8020284

Muñoz García, A., & Atanasio Guisado, A. (2015). Plan de Ordenación de restauraciones del conjunto monumental del Real Alcázar de Sevilla [Restoration plan for the monumental complex of the real Alcazar of Seville]. *Apuntes Del Alcázar de Sevilla*, *16*, 88–173.

Norin, V., Golovina, S., & Tikhonov, Y. (2019). Application of three-dimensional technologies in restoration of architectural decor elements. *E3S Web of Conferences*, *135*, 1–12. https://doi.org/10.1051/e3sconf/201913503007

Ortega-Ramírez, J., Bano, M., Villa Alvarado, L. A., Medellín Martínez, D., Rivero-Chong, R., & Motolinía-Temol, C. L. (2021). High-resolution 3-D GPR applied in the diagnostic of the detachment and cracks in pre-Hispanic mural paintings at 'Templo Rojo', Cacaxtla, Tlaxcala, Mexico. *Journal of Cultural Heritage*, *50*, 61–72. https://doi.org/10.1016/j.culher.2021.06.008

Pavón Maldonado, B. (1973). *Arte toledano: islámico y mudéjar* [Toledo Art: Islamic and Mudejar]. Instituto Hispano-Árabe de Cultura.

Ramírez Eudave, R., & Miguel Ferreira, T. (2021). On the suitability of a unified GIS-BIM-HBIM framework for cataloguing and assessing vulnerability in Historic Urban Landscapes: A critical review. *International Journal of Geographical Information Science*, *35*(10), 2047–2077. https://doi.org/10.1080/13658816.2020.1844208

Ritterbach, L., & Becker, P. (2020). Temperature and humidity dependent formation of CaSO4·xH2O (x = 0 … 2) phases. *Global and Planetary Change*, *187*(*1031320313*), 1–11. https://doi.org/10.1016/j.gloplacha.2020.103132

Rodríguez Rodríguez, I. (2019). Sistema de gestión del real alcázar de sevilla [Management system of the royal alcazar of Seville]. *Apuntes Del Alcázar de Sevilla*, *19*, 144–161.

Rubio Domene, R. (2010). *Yeserías de la Alhambra. Historia, técnica y conservación* [Alhambra plasterwork. History, technique and conservation]. Patronato de la Alhambra y Generalife. University of Granada.

Sánchez-Aparicio, L. J., Del Pozo, S., Ramos, L. F., Arce, A., & Fernandes, F. M. (2018). Heritage site preservation with combined radiometric and geometric analysis of TLS data. *Automation in Construction*, *85*, 24–39. https://doi.org/10.1016/j.autcon.2017.09.023

Sánchez-Aparicio, L. J., Masciotta, M.-G., García-Alvarez, J., Ramos, L. F., Oliveira, D. V., Martín-Jiménez, J. A., González-Aguilera, D., & Monteiro, P. (2020). Web-GIS approach to preventive conservation of heritage buildings. *Automation in Construction*, *118*, Article 103304. https://doi.org/10.1016/j.autcon.2020.103304

Serrano Rodríguez, J. (2019). *Actuaciones de urgencia de conservación preventiva y mantenimiento de las yeserías del palacio mudéjar del Real Alcázar de Sevilla* [Emergency actions for preventive conservation and maintenance of the plasterworks of the Mudejar palace of the RAS]. Patronato del Real Alcázar de Sevilla.

Soler, F., Melero, F. J., & Luzón, M. V. (2017). A complete 3D information system for cultural heritage documentation. *Journal of Cultural Heritage*, *23*, 49–57. https://doi.org/10.1016/j.culher.2016.09.008

Soler, F., Torres, J. C., León, A. J., & Luzón, M. V. (2013). Design of cultural heritage information systems based on information layers. *Journal on Computing and Cultural Heritage*, *6*(4), https://doi.org/10.1145/2532630.2532631

Stefani, C., Brunetaud, X., Janvier-Badosa, S., Beck, K., De Luca, L., & Al-Mukhtar, M. (2014). Developing a toolkit for mapping and displaying stone alteration on a web-based documentation platform. *Journal of Cultural Heritage*, *15*(1), 1–9. https://doi.org/10.1016/j.culher.2013.01.011

Sumeyye Sena Bastem, & Cekmis, A. (2022). Development of historic building information modelling: A systematic literature review. *Building Research & Information*, *50*(5), 527–558. https://doi.org/10.1080/09613218.2021.1983754

Swaileh, W., Jordan, M., & Kotzinos, D. (2022). Lecture notes in computer science. DAS 2022. 13237, 629–643. https://doi.org/10.1007/978-3-031-06555-2_42

Tabales Rodríguez, MÁ. (2005). El patio de las doncellas del palacio de pedro I de castilla. Génesis y transformación [The courtyard of the maidens in the palace of pedro I. Genesis and transformation]. *Apuntes Del Alcázar de Sevilla*, *6*, 7–43. https://www.alcazarsevilla.org/wp-content/pdfs/APUNTES/apuntes6/restauracion1_04/contenidos_res1.html

Tabales Rodríguez, M. Á, Alejandre Sánchez, F. J., Blasco López, F. J., & Vargas Lorenzo, C. (2017). 14C chronological data and thermoluminiscence of Islamic tapiales of the Real Alcazar of Seville. *digitAR - Revista Digital de Arqueologia, Arquitectura e Artes*, (4), 51–57. https://doi.org/10.14195/2182-844X_4_6

Tejedor, B., Lucchi, E., Bienvenido-Huertas, D., & Nardi, I. (2022). Non-destructive techniques (NDT) for the diagnosis of heritage buildings: Traditional procedures and futures perspectives. *Energy and Buildings*, *263*, 1–22. https://doi.org/10.1016/j.enbuild.2022.112029

Tormo Esteve, S. (2016). Aplicación de la Termografía Infrarroja como ensayo no destructivo (END) en la restauración del patrimonio arquitectónico [Application of infrared thermography as non-destructive testing (NDT) in the restoration of architectural heritage]. *Papeles Del Partal*, *8*, 69–82.

Torres-González, M., Alejandre, F. J., Flores-alés, V., Calero-castillo, A. I., & Blasco-lópez, F. J. (2021). Analysis of the state of conservation of historical plasterwork through visual inspection and non-destructive tests. The case of the upper frieze of the Toledanos Room (The Royal Alcázar of Seville, Spain). *Journal of Building Engineering*, *40*(10231402314), 1–14. https://doi.org/10.1016/j.jobe.2021.102314

UNESCO World Heritage Committee. (1987). *Convention concerning the protection of the World Cultural and Natural Heritage. Report of Eleventh Session*. http://whc.unesco.org/en/list/383

van Balen, K., & Vandesande, A. (2013). *Reflections on preventive conservation, maintenance and monitoring by the PRECOM3OS UNESCO Chair*. Acco.

Villanueva Domínguez, L., & García Santos, A. (2001). Manual del yeso [Plaster manual]. In *ATEDY-DOSSAT 2000*. CIE Inversiones Editoriales.

Vinuesa, T., Troitió Torralba, MÁ, Salmerón Escobar, L., Pérez de la Torre, P., & M, R. (2020). Public tour of the royal Alcázar of Seville: Basis for the functional reorganisation of the monumental ensemble. *Apuntes Del Alcázar de Sevilla*, *20*, 127–169.

Xiao, W., Mills, J., Guidi, G., Rodríguez-Gonzálvez, P., Gonizzi Barsanti, S., & González-Aguilera, D. (2018). Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals. *ISPRS Journal of Photogrammetry and Remote Sensing*, *142*, 389–406. https://doi.org/10.1016/j.isprsjprs.2018.01.001

Yang, X., Grussenmeyer, P., Koehl, M., Macher, H., Murtiyoso, A., & Landes, T. (2020). Review of built heritage modelling: Integration of HBIM and other information techniques. *Journal of Cultural Heritage*, *46*, 350–360. doi:10.1016/j.culher.2020.05.008

Zalamea Patino, O. P., Van Orshoven, J., & Steenberghen, T. (2018). Merging and expanding existing ontologies to cover the Built Cultural Heritage domain. *Journal of Cultural Heritage Management and Sustainable Development*, *8*(2), 162–178. https://doi.org/10.1108/JCHMSD-05-2017-0028