Pathology detection for HBIM application on a Byzantine church in Axos village in Crete, Greece

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Abstract: The introduction of digital photogrammetry techniques in recent years regarding monumental structures brought about significant changes in their survey and representation. Apart from the obvious benefit in geometric accuracy and the visual qualitative information, useful for archaeologists and architects, deliverables can also be used by a number of experts, like civil engineers and restorers, having been processed accordingly, aiming in a future usage in BIM technology. Building Information Modeling (BIM) is the most modern, effective and functional technology applied in the AEC field nowadays, since it has numerous possibilities in combining data of multiple kinds in a readable format accessible by different scientists and experts. Research and discussion on Heritage BIM, an effort of describing the application of BIM technology in historic buildings, is being carried out at an increasing scale lately, as most countries realise that preservation of cultural heritage is closely related to the future and prosperity of humanity. By its definition BIM seems to be ideal for issues regarding existing structures and monuments in particular, because it has the ability to integrate different type of data, from architectural design to historical and structural information, as well as pathology and intervention techniques. The paper presents pathology detection using photogrammetry, the documentation and classification of existing damages on a byzantine church on the island of Crete in Greece, providing the possibility of implementing the selected data to the HBIM model of the monument. The specific monument is selected due to its significant value frescos and a method of pathology diagnosis using photogrammetric tools will be analysed.

Keywords: *Byzantine Architecture—Photogrammetry—Laser Scanning—Cultural Heritage—HBIM*

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Introduction

Building Information Modeling (BIM) is a revolutionary technology that is characterized as the opportunity of the AEC (architecture, engineering and construction) industry to move to the digital era and improve the collaboration amongst the partners of this industry by exploiting Information and Communications Technologies (ICT) (Eastman, 2008). BIM provides automation capabilities for more integrated communication, data exchange and sharing between project actors within a virtual 3D environment (Gu and London, 2010). Implementing Building Information Modelling may be an approach to enhancing collaboration, attempting to reduce fragmentation. BIM connects different tools as a repository framework and allows queries on building conditions, time management, and cost estimation to plan effective and sustainable interventions (Bruno et al., 2018). In a relatively limited time, the implementation of BIM has developed from a 3D model (basic space dimensions) to a 4D (time) and 5D (cost) model, giving the ability to stakeholders to have access to and control not only geometric, but also non-geometric information, contributing to a more secure and cost-effective decision-making. The designed virtual models are directly linked with databases of all information in order to achieve the best possible management in the buildings' life cycle, from the design phase, construction, management, maintenance to its demolition. Using shared neutral exchange formats, like Industry Foundation Classes (IFC) and cityGML (city Geographic Markup Language) all data and information can be exported and used accordingly by all parties involved (O'Keeffe and Bosché, 2015). Therefore, the utilization of BIM as a tool for all relative stakeholders (scientists from multidisciplinary fields, construction, and real estate companies etc) is going to grow bigger. Already, many countries such as UK have introduced BIM technology as an obligatory construction process for public buildings, due to its regulatory requirements (Ewart and Zuecco, 2019).

Acknowledging the numerous applications and possibilities of BIM technology to combine various data in a single file, accessible to different scientists and experts, researchers have been trying lately to apply BIM on buildings of historic value (Murphy, 2012). Heritage or Historic Building Information Modelling (HBIM) is a new approach to create intelligent three-dimensional models and databases of historic buildings that integrate information and data, attributing in processing architectural designs (Maxwell, 2016), static analysis (Castellazzi et al., 2015), seismic vulnerability (Mondello et al., 2019), pathology (Dore et al., 2015) (Turco et al., 2017), ICT computing, geomatics, cultural heritage documentation (García et al., 2018), architectural intervention techniques (Oreni, 2013) and maintenance practice. However, despite the aforementioned pros that BIM can offer, it still remains in a research phase, with limited use by authorities in charge of conservation (Fai et al., 2011) (Fregonese et al., 2017). The slow integration and implementation of BIM in the field of restoration of monuments could be attributed mainly to the variety and complexity of heritage assets (García-Valldecabres et al., 2016), as well as to the lack of precise regulations and guidelines (Arayici and Tah, 2007, Volk et al., 2014).

The application of BIM in a structure of cultural heritage (CH) comprises the following steps (scan-to BIM process): a) Historic-architectural-structural survey b) Data capture c) Data Processing d) Object recognition (semantics) e) BIM Modeling (Volk et al., 2014). Each of these steps is still under development, underlining that the method followed every time is customizable by the building/site and its special specifications.

The analytical and theoretical research regarding historic data is of high importance when dealing with a CH building, contributing to right decision making by the researchers in following the best suitable survey technique, having studied structure's construction phases and changes through time, in order to limit the time of the work on site.

In a digital documentation and 3D modelling project, the basic goal is to have an accurate and photo-realistic digital representation of the structure, to support activities like investigation and interpretation as well as for educational or cultural benefits. Accurate data capturing and survey techniques is usually done using photogrammetry and/or Laser scanning (Remondino and Rizzi, 2010). The choice of the best approach depends on required accuracy, object dimensions, location constraints, system's portability and usability, surface characteristics, working team experience, project's budget, final goal, etc (Aveta et al., 2017). Today RPAS (Remotely Piloted Aircraft System) and TLS (Terrestrial Laser Scanning) survey can produce high quality point cloud and 3D model in archaeological sites, in limited time and with satisfying metric accuracy.

Data processing, unlike capturing, is a time-consuming, complex procedure that requires a lot of working hours by specialists, to produce an accurate 3D model of the scanned building. During processing, point cloud data that derives from images (photogrammetry) or laser is registered, aligned and merged into the same coordinate system. Manipulation of the scanned data includes noise removal and cleaning point cloud from irrelevant information. The procedure, according to the size of the structure, the desired accuracy and further requirements, may take significant computing time, due to large volume of data and limitations on computing performance. The point cloud data is finally converted in forms that can be used by CAD software for minimising the necessary disk space and computers' high-end specifications.

Object recognition and BIM modelling is the last sector where all gathered data is classified and integrated to a 3D digital description of the structure, its site and related geographic information system (GIS) context. During this process, the building is comprised with attributes defining the properties of each object as well as their relationships, differentiating the process from CAD, transforming objects from graphical entities (lines, arcs, circles) to semantic elements (walls, beams, domes, etc). The final model comprises all information in one repository in an integrated data environment, ensuring consistency, accuracy and accessibility of data. Nevertheless, semantic classification is under scientific research, as all CH structures, even buildings of the same period or type, have special features that make them unique. Therefore, a strict classification under special regulations and guidelines is not possible to be set, since each case study is different from the other, demanding a different approach and method of analysis. The standard classification most BIM software use in managing architectural elements is unable to fulfil CH needs, because of the complexity of historical assets and their unique architectural, structural, and artistic character, which requires a multi-disciplinary approach, involving different scientists and a specialised way of working. Research work is done towards usability and flexibility in semantic data management, in order to satisfy the case-specific requirements and meet the needs of all parties involved.

In this paper a research case of documentation of structural pathology for HBIM implementation on the byzantine church St. Ioannis Prodromos in Crete, Greece is presented, analysing the process of historical analysis, data capture using laser scanning and photogrammetric tools and documentation, proposing a method for pathology diagnosis and classification to be used in an HBIM application in the future.

Methodology

Historical analysis – documentation

The church of St. Ioannis Prodromos is located in Crete, at Psiloritis mountain, in Axos village. Axos is located to the municipality of Mylopotamos, in Rethymno's county, 46 km away from the city of Rethymno and 48 km from Heraklion, at an altitude of 500 m, approximately. The Church is located approximately at 150 m. easter of the current settlement of Axos on a hill. The surrounding area is listed as a protected historical location by the Hellenic Ministry of Culture, whereas St. Ioannis is the most well-preserved byzantine church in the settlement of Axos. Although a written proof of chronological reference has not been found yet, according to Em. Borboudakis, archaeologist and ex Director of Byzantine Ephorate in Crete, based on his study of the internal frescos, the church was probably built in the first half of 15th century.

Typology – architectural analysis

St. Ioannis Prodromos is a single-aisle arched church with two internal stone arcs for additional structural support and a duo-pitched roof with byzantine tiles which is not the original, since the roof of the temple was replaced in the '90s (Fig. 1). The width of the church externally is 5.15 m and its length, up to the arch of the sanctuary, is 8.90 m and with the arch is 10 m (Fig. 1). The width of its interior is 3,62 m. Sanctuary's arch was built on the remains of an older church, which today is preserved at the level of its foundation, 0.20 m over the ground surface. One of the most interesting aspects of this church is a byzantine tile (sleeper), which can be found at the right and left side of the sanctuary's arch at a height of 2.46 m, which has been placed inside the stone structure and was used as a sink, for the elimination of water and moisture, trapped between the roof and the masonry.

In the interior, area consists of the the main temple on the west side and the Sanctuary. Entrance is located on the west façade, having a stone architectural part as a doorstep, probably re-used from a nearby ancient monument of dimensions 1.10 × 0.50 m. On the perimeter of the main temple there is a stone-built desk covered with concrete. Church is fully painted with frescos representing numerous instances from St. Ioannis' life, as well as other Christian-Orthodox ceremonial subjects and Saints images. One of the most interesting and important aspects of the church besides its frescoes is the mosaic found on the southeastern side of the floor. This element was significant to the whole study, as it helped in the dating procedure of the monument. The remains of the mosaic, after being cleaned, were imprinted with millimeter accuracy, giving the possibility, after an extensive study of its themes and style, to identify that it was created in the byzantine period.

Fig. 1. SouthWestern view of St Ioannis Prodromos in Axos, Crete.

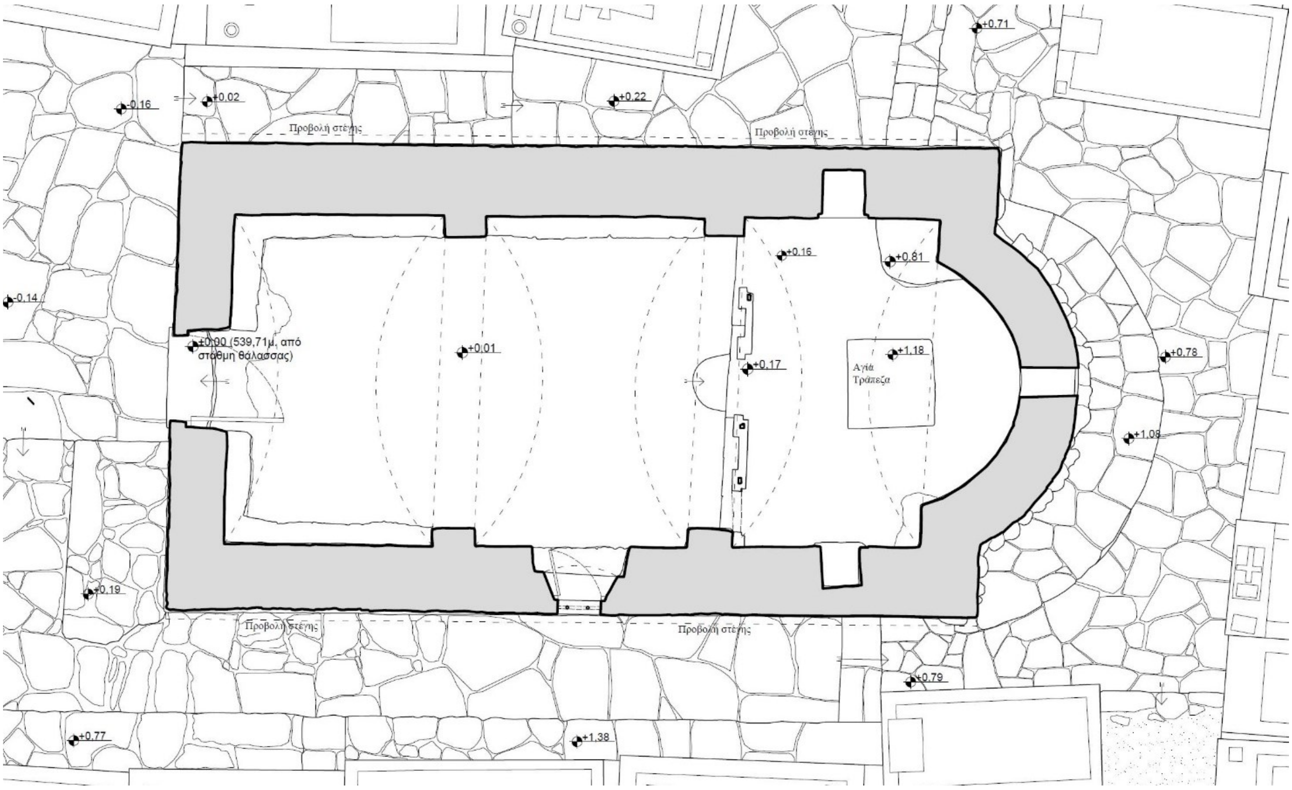


Fig. 2. Floor plan of St Ioannis Prodromos in Axos, Crete.

Pathology diagnosis using laser scanning and photogrammetry optimization and filtering

On site survey – laser scanning- TLS data acquisition

The architectural survey was executed by using Faro's 3D Multisensor Focus Laser Scanner. Planar and spherical targets were used to contribute and control the point cloud registration. Two planar targets were positioned on each wall (for a total of 8 targets) and ten spherical targets were placed distributed so as every scan included at least 3 of them for better results. The planar targets, measured with a total station, may have the dual role of helping point clouds registration process and georeferenced the data in the local reference system (Lo Brutto et al., 2017). The number of positions, and therefore the scans, depend on each space or object and their selection is made in order to avoid shadows and hidden spots. If there are obstacles or overlapping objects, the number of scans must be increased, so that under different angles would be scanned each item, and included in the final model. In this particular case, the accuracy was determined at 6,15 mm and included four repetitions per scan (England, 2018). Finally, 9 scans were produced and the whole procedure was carried out, allowing the engineers to gather all data needed for a restoration study, on a single working day. After scanning process, laser scanner took photos and started the colorization of the scanned points, using the built-in self-adjusting color digital camera, capable of producing high-resolution panoramic images of up to 70 megapixels. The optical beam of the camera is coaxial to the laser beam; thus, scanner can photograph simultaneously by scanning the object and attaches it to the cloud points of real chromatic texture (Aveta et al., 2017). Data was stored on an SD memory card, so when the field tasks were completed, it was transferred to the workstation.

Point cloud optimization – mesh modelling

Faro Scene was used for point cloud optimization, smoothing and filtering, as well as creation of orthophotos, while highly accurate architectural designs were made using Bentley Pointools View, saving a significant amount of effort and time comparing it to traditional methods. Although the initial intention of the study included using Revit for the whole project, all architectural designs were finally made in AutoCAD, because the highest possible level of accuracy was needed as far as geometry was concerned. A model in Revit Architecture was created based on AutoCAD designs on a second phase of the project, as described on the following chapter. The final 3D point cloud model, which is comprised of seven hundred and eighty (780) million points, had the accuracy needed for further processing and design drawing. The final product allows the engineer to have all possible aspects and views of the monument, like sections and axonometric models, very useful for the architectural, structural and conservation studies (Fig. 3).

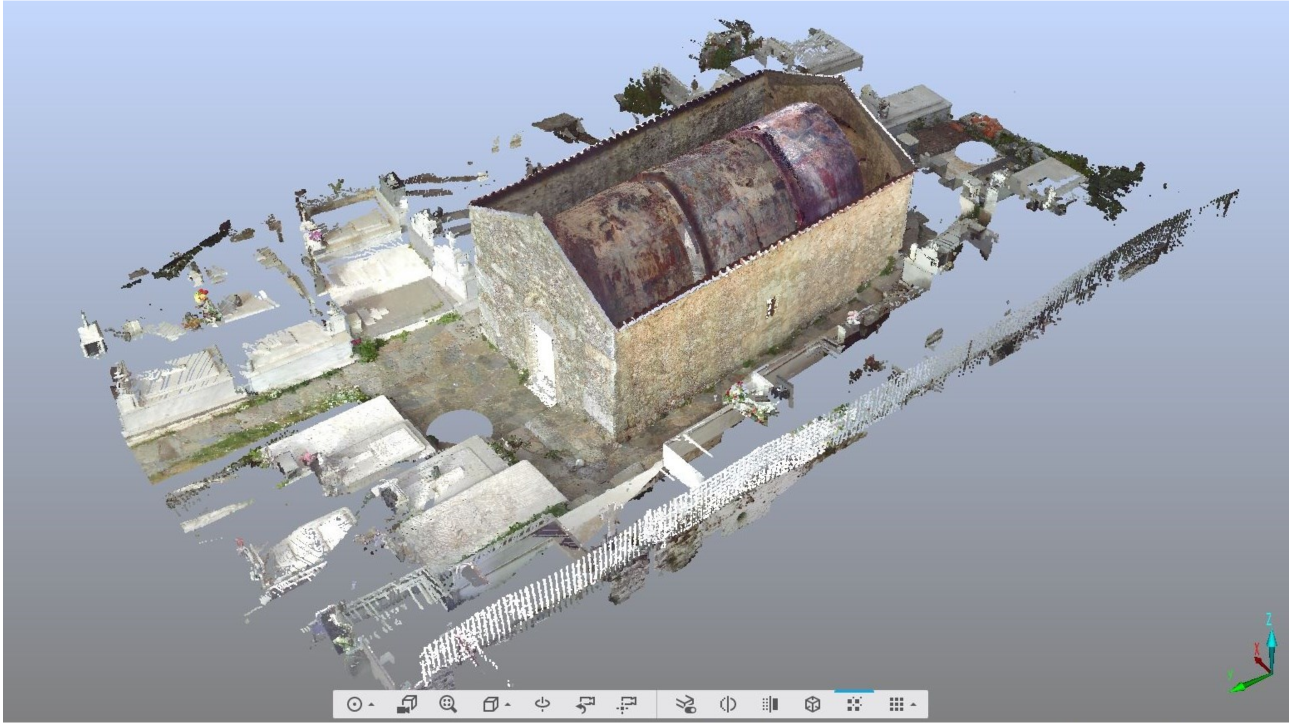


Fig. 3. 3D Digital model- Pointcloud – Axonometric view of the church (© Authors).

Pathology diagnosis

The data from the on-site work permitted the detailed study of the monument in the office. The church's masonry is covered with thin lime-based plaster, while on several areas there have been more recent cement interventions both in mortars and in plaster. Aesthetic problems are caused by large amounts of concrete mortar, which have been used at the end of the pediment for reasons of roof waterproofing.

In-situ research revealed that the church was built on the remains of an older Christian church and has undergone some minor interventions throughout its life history. However, nowadays it is facing various problems regarding the deterioration of materials i.e. due to environmental causes (humidity) and structural integrity due to damages caused by earthquakes taking place in the area. After evaluating all information gathered and having studied monuments' typology and special characteristics, research focused on documenting two different categories of pathology issues: *structural* and *non-structural* (aesthetic) ones.

Pathology diagnosis for structural engineers demanded the highest possible level of accuracy regarding cracks, differences in the shape of structural elements, severe humidity issues that affect stability, etc. Therefore, a methodology using digital processing of selected orthophotos was followed. This technique was chosen as the best applicable one since the whole church was covered with frescos inside, making existing cracks difficult to mark and notice. This phenomenon was worsened by the high level of humidity which had created large blackish areas on the facades. Digital processing including removal of the RGB filters and controlling of orthophotos' level of intensity was carried out in all interior surfaces, making frescos disappear and cracks appear clearly on the walls and arches (Fig. 4, Fig. 5). Architectural designs of pathology were finally made in AutoCAD using Bentley Point Tools for numerous sections, because the highest possible level of accuracy was needed as far as geometry was concerned. This methodology allows civil engineers to have all the necessary data concerning structural problems and by combining them to their structural analysis to come to helpful conclusions and suggestions regarding measures for restoration and strengthening of the monument, having spent a limited time on the specific site. Taking into account that this data can be used by public officers of e.g., a Ministry or a Municipality, whose presence all over the country to inspect all monuments is almost impossible, this technique could contribute in having immediate results and estimation regarding integrity of each structure.

Fig. 4. Orthophoto of the north facade of St Ioannis Prodromos Church in Axos.

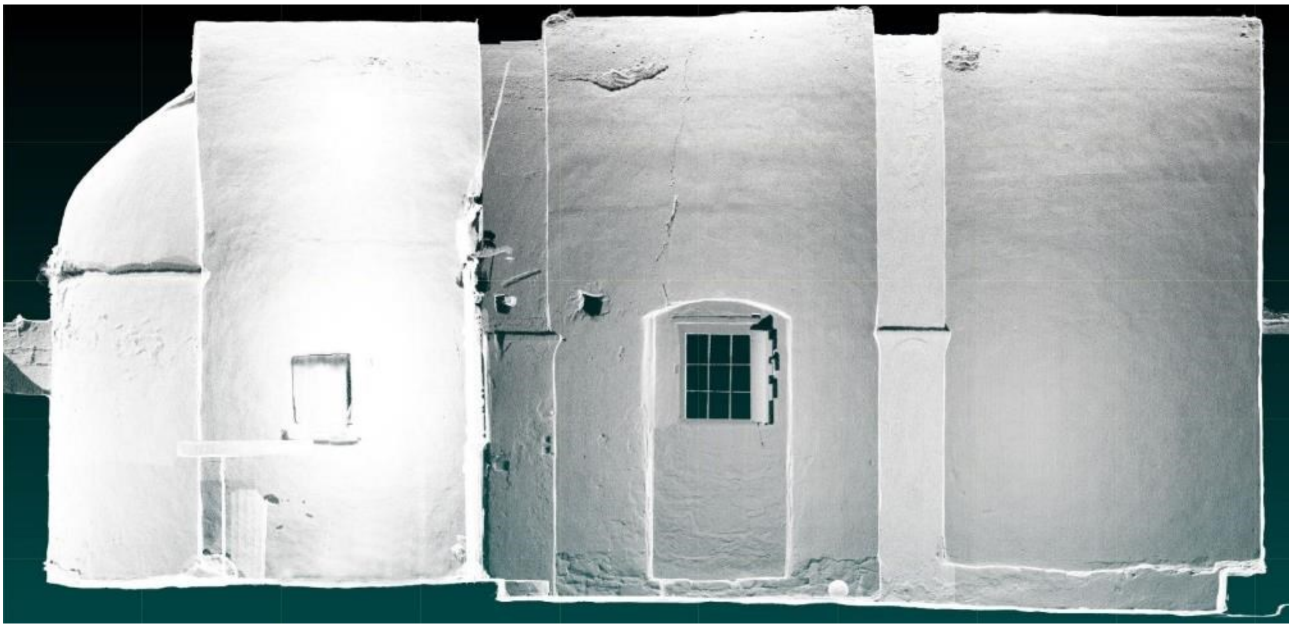
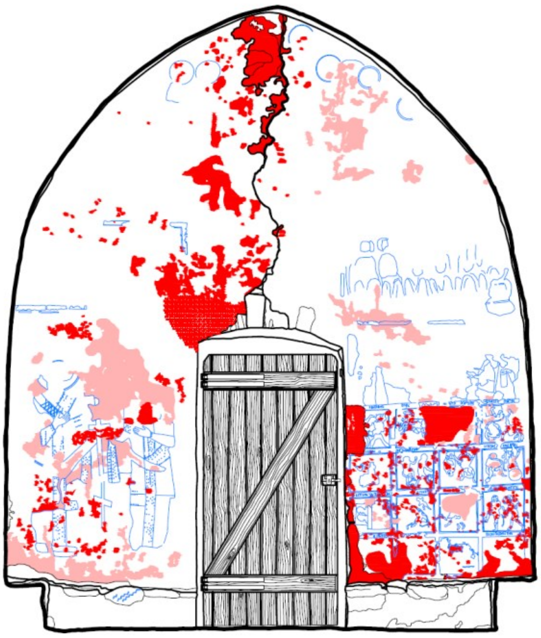


Fig. 5. Orthophoto of the north facade of St Ioannis Prodromos Church in Axos, without RGB filters, used for crack detection.

At parallel, conservators used orthophotos and digital processing in order to document frescoes pathology (non-structural problems). Since their significance was considered of high importance for the restorers, a more specialised approach was followed, that required detailed drawings for the frescoes of each façade, where pathology issues were documented in full detail (Fig. 6).

a



b

Fig. 6. West internal façade a) Orthophoto b) AutoCAD drawing with pathology mapping.

Pathology documentation and classification

Final documentation on pathology was implemented after evaluating all characteristics of the monument, leading to the creation of a database in Microsoft Excel, to be used by a data management tool in any of the most known commercial BIM applications (Bruno and Roncella, 2019). Each structural and non-structural member of the model was classified according to this methodology, having the ability to add all relevant photos, sketches, historical data for every one of them to the database.

Focusing on pathology, a distinct separation on structural and non-structural problems was implemented. After a thorough evaluation by both architects and civil engineers, all cases were classified in 16 categories, regarding both serious structural problems, like cracks and collapsed areas, as well as less important ones, but still significant, like humidity or missing plaster (Fig. 7) (Turco et al., 2017), (Malinverni et al., 2019). Well-preserved areas were also marked, in order for engineers to be able to have a first but still established opinion about structures' current condition, allowing best possible decision-making by restorers and helping eliminate mistakes regarding the cost and planning of restoration works. Documentation was made on the architectural designs, marking each area with its diagnosed pathology, so as to be attributed visually to the elements of the 3D model.

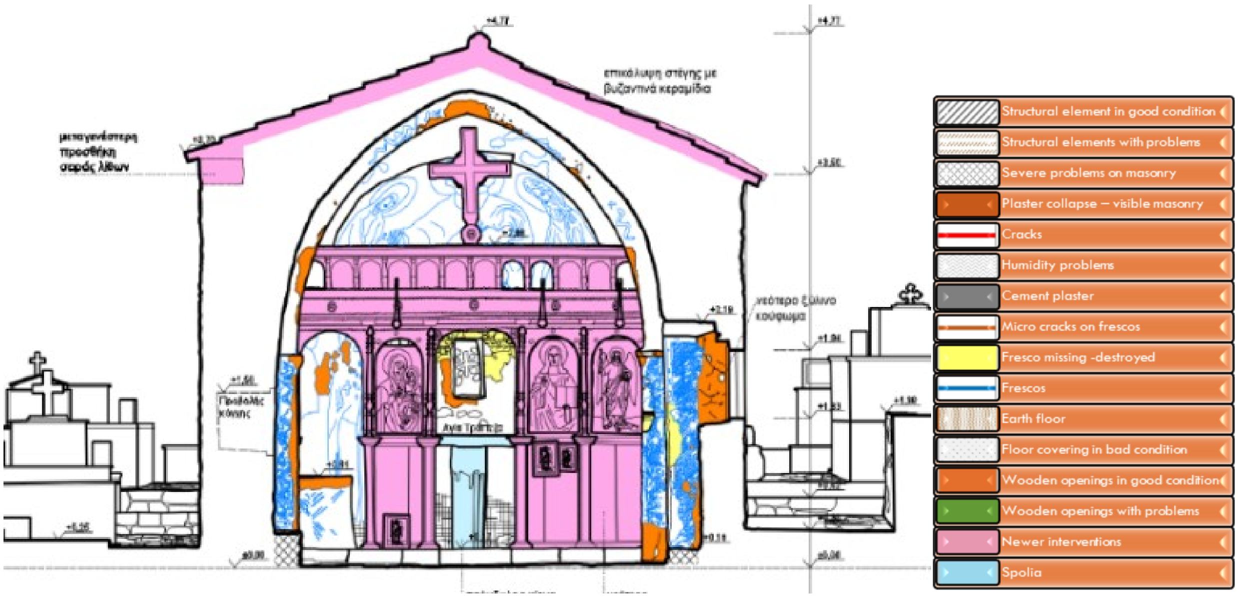


Fig. 7. Structural pathology documentation.

In a second phase of the project, a model in Revit 2021 Architecture was created, using all existing designs and information (Fig. 8a, b). Wall and floor architectural elements were used for the creation of masonry, vault structures and grounding area, while the materials of the Revit 2021 library were used (Fig. 8c, d), awaiting the analysis of the mechanical characteristics for further expansion of the attributes. The filling material between the vault and tiles was modelled as well, adding to the constructional accuracy of the model. All information regarding pathology, photos, pathology designs, etc, are added as pictures linked to each façade, while the excel database is being combined to the Revit model.

Further planning of this on-going project, includes adding numerical data on the model, such as crack width and other characteristics (position, cause of appearance, etc) linked to the structural model of the monument which has been created in SAP (Fig. 9) and locates the «sensitive»—more vulnerable areas, for structural engineers to be able to assess the further deterioration of the construction and propose on time the best measures necessary in case of emergency or danger of collapse.

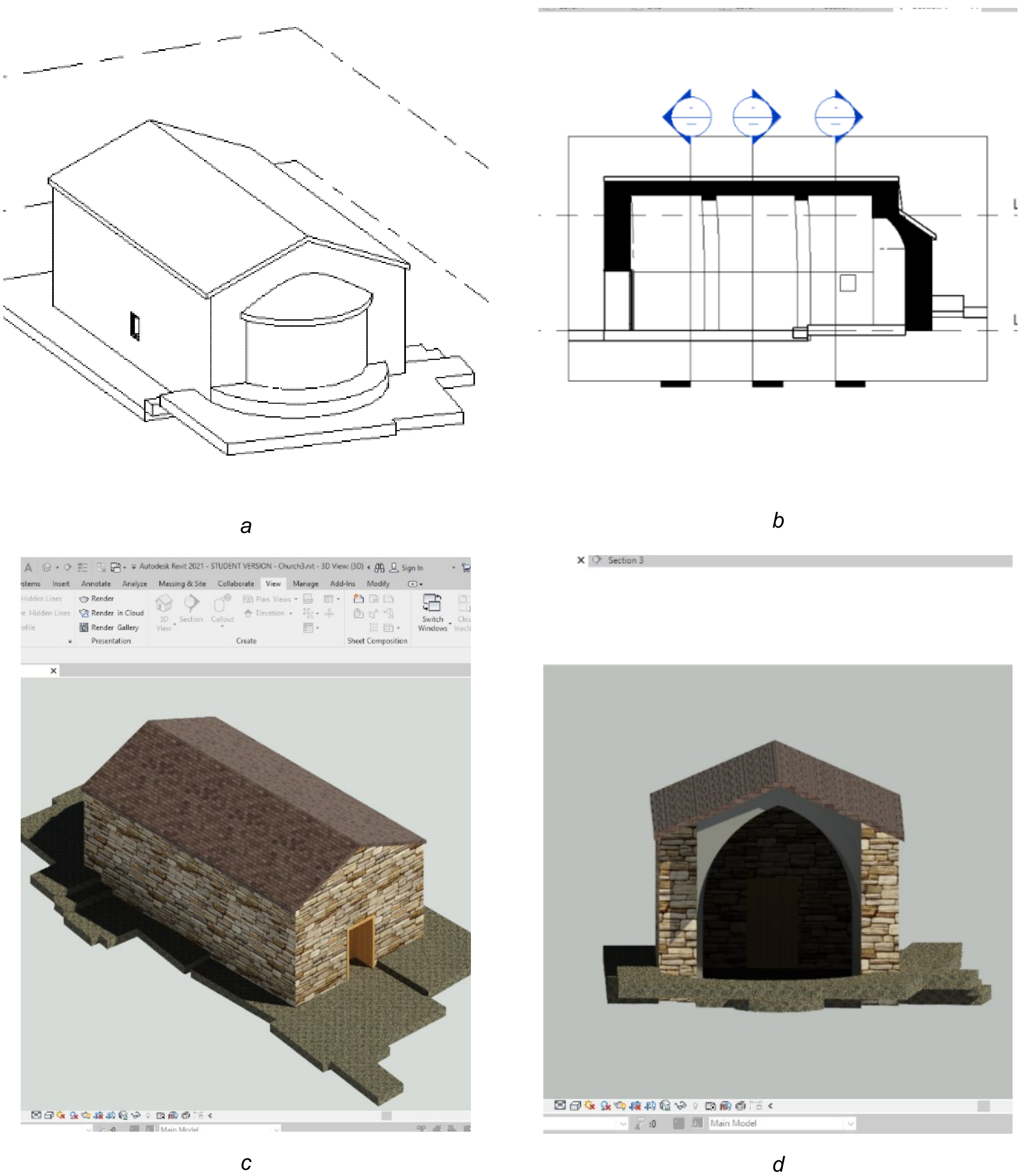


Fig. 8. Model of St Ioannis in Revit 2021 Architecture.a) 3D SE view b) Cross section c) Photorealistic NW view d) Cross section where different material is shown.

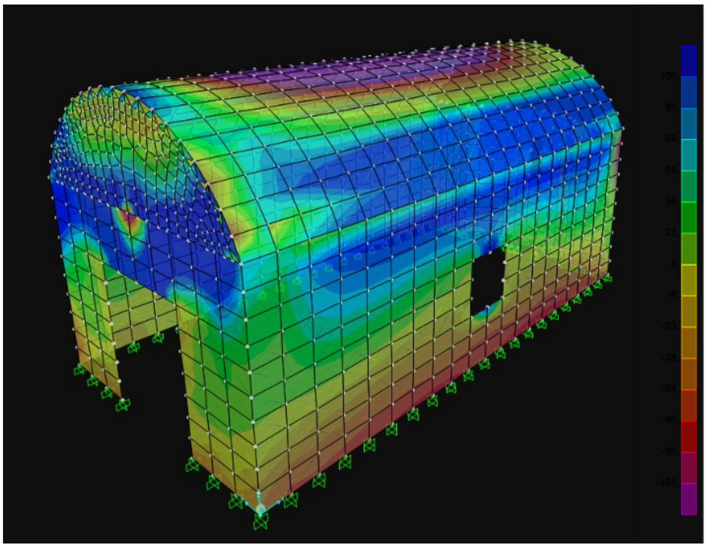


Fig. 9. Finite element model in SAP2000.

Non-structural (aesthetic) problems focused on frescoes, where façades were separated in frames for every form, linked to a list with the name of the Saint or the Christian expression that can be further expanded using semantics regarding orthodox icon themes. Pathology was classified in 16 categories, regarding only the problematic areas and including issues like micro cracking, missing colours, biological damage, etc (Fig. 10). It is important to note that in this case a close collaboration with experienced conservators was necessary, for a full and thorough documentation, that could save both time and money in the restoration process.

This methodology allows scientists in the field of cultural heritage restoration to document accurately a historic building and collect pathology information that can be used on an HBIM central repository, underlining that the use of Excel database that was followed in this methodology can be expanded in the future by combining Linked Open Data solutions and IFC technology along with the Revit model.

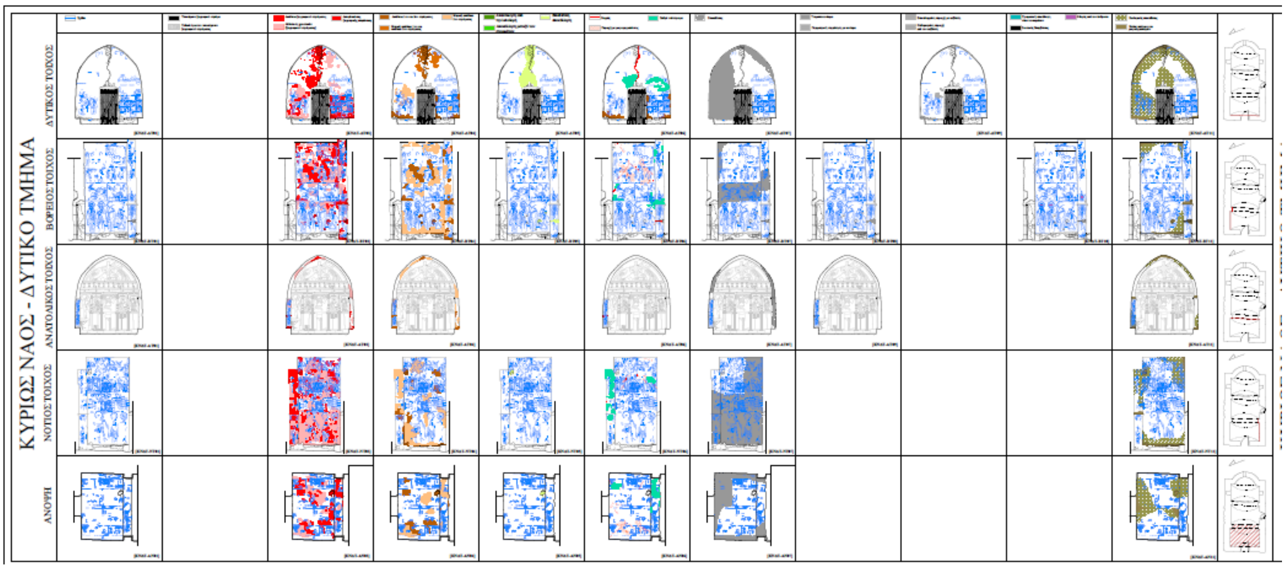


Fig. 10. Frescoes pathology documentation.

Semantics

In the field of CH, the integration of semantic data with 3D models using BIM technologies (Scianna et al., 2014) allows to preserve an exhaustive level of information of the cultural good available for all stakeholders. In this particular case, a semantic classification was implemented, trying to categorise every structural and architectural member, according to VRA Core 4.0 standards and using controlled vocabulary databases, especially the Getty vocabulary program (Fig. 11).

WORK					
VRA Core Element	XML Element	XML Child Element	XML Attribute	XML Child Element	DATA
-	-	-	-	-	-
TITLE	title				Church of St Ioannis Prodromos in Axos
-			type		cited
-					
WORK TYPE	worktype				churches (buildings)
			vocab		AAT
			refid		300007466
CULTURAL CONTEXT	culturalContext				unknownGreek Orthodox
			vocab		ULAN
			refid		500355123
DATE	date				15th century
			type		creation
			latestDate		1450
DESCRIPTION	description				Church of St. Prodromos is the best well-preserved byzantine church in the settlement of Axos. It is a single-aisled arched church with two internal stone arcs for additional structural support and a duo - pitched roof with byzantine tiles
LOCATION					
	location				Crete
		type			administrative
			name		Crete
				type	inhabited place
				vocab	TGN
				refid	7012056
	location				Axos
		type			administrative
			name		Axos
				type	inhabited place
				vocab	TGN
				refid	7233983
MATERIAL					
	material				masonry
			type		medium

Fig. 11. Semantic classification

Conclusions

In this paper, a method of pathology detection using photogrammetry and an attempt of documentation of structural and non-structural pathology of a byzantine church, was presented. Data processing required a multidisciplinary approach and was highly demanding. Documentation was made using human intervention on architectural designs, providing the possibility of implementing the selected data to the HBIM model of the monument. The proposed methodology starting from historical analysis, 3D data survey, documentation and classification of pathology can be used in creating the necessary parameters in a model of a byzantine monument in an HBIM platform, having the possibility to be expanded and enriched following the example of worldwide development in semantic data management for such buildings, like the MonArch[1] project or the Baureka[2] platform. Nevertheless, the acquired data can be very useful in the future restoration studies as well as in the actual working phase, saving a significant amount of time and money, by offering accurate and detailed information.

In addition, the methodology proposed for crack detection by digital processing of orthophotos can be used not only on pathology survey but also on the monitoring of the structure through time, arriving at significant conclusions about the gradual deterioration of a building and the necessity of urgent interventions. This way, researchers could reach to accurate results, having spent the minimum possible time on site and contribute to the HBIM documentation of cultural heritage.

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[1] https://wp.uni-passau.de/monarch/
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