Representation of the Hagia Sophia view. Imaged by author İzzettin Kutlu.

Critical analysis and digital documentation of the transformations of heritage buildings

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Abstract: Trabzon Hagia Sophia Mosque symbolizes significant cultural heritage with its historical diversity and distinctive architectural features. Today, this building is remarkable for its cultural transformation and historical layers. The study aims to address the transformation processes of the Hagia Sophia Mosque in the light of international conservation criteria, to understand the history of the building and to reveal the digital perspectives of this historical place. The study comprises a four-stage process: (1) investigating the building's history through a literature review, (2) obtaining visual and technical data through fieldwork, (3) conducting a transformation analysis and generating a three-dimensional measured model, and (4) providing evaluations and recommendations on the building's transformation and digital modeling in alignment with conservation criteria. The digital model of the building as a result of the study will be part of the preservation of such an important piece of cultural heritage for future generations. The study emphasizes the need for more effective integration of digital modeling techniques in conservation and documentation studies, extending from Hagia Sophia to various cultural heritage sites.

Keywords: Historical buildings; Cultural heritage; Digital documentation; Hagia Sophia Mosque.

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1. Introduction

Cultural and natural heritages face threats from various natural and human factors, raising concerns about their sustainable conservation. Nations possessing cultural and natural heritage often grapple with insufficient economic, scientific, and technical resources, potentially limiting effective heritage conservation (Bogdan et al., 2022; Mendoza et al., 2023; Ergün & Halaç, 2021). Hence, all nations are now responsible for contributing to scientific research and innovative techniques in cultural heritage conservation. These heritage sites have become more than simply places where historical information can be obtained, they have become a means of intercultural dialogue, mutual understanding and communication (Kutlu & Bekar, 2021; Remondino & Rizzi, 2010; Saha et al., 2021). The critical periods of human history, the evolution of art and the traces of social change can be found in these sites (Okech, 2010). Therefore, cultural heritage sites represent not only the memory of a society, but also a global heritage.

Preserving and passing on cultural heritage, the focus of conservation efforts, has become a fundamental responsibility for contemporary societies and a basic right for future generations (Sürücü & Başar, 2016). The preservation of cultural heritage is a universal issue. Disciplining the preservation and passing on of cultural heritage through various laws and regulations undoubtedly plays an important role in the success of these actions. International conservation criteria have become a world policy in the preservation and passing on of cultural heritage to future generations and the success achieved in this regard has become one of the indicators of modernisation. For the sustainable preservation of cultural heritage, it is crucial to conduct interventions guided by established conservation criteria and to document the changes and transformations from the past to the present for future generations. Many of the declarations containing conservation criteria include articles on the importance of documenting cultural heritage. Utilizing new and contemporary documentation techniques with today's evolving technology in cultural heritage documentation provides practical results. Since the Venice Charter (1964), International Council on Monuments and Sites (ICOMOS) has recommended the utilisation of all sciences and techniques that can contribute to conservation. Similarly, the Council of the European Union (EU) adopted a resolution on multimedia in the field of cultural conservation (EU Council, 1995). ICOMOS published The ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites on the interpretation and presentation of cultural heritage sites in 2008 (ICOMOS, 2008). All these principles and decisions encourage the use of current technologies in conservation. Based on this perspective, the transformation process of historical buildings and the importance of documenting of the historical building in the light of international conservation criteria were discussed and digital modelling and documentation techniques were focused on as a contemporary approach.

The meticulous documentation and preservation of cultural heritage is of great importance not only for countries but also for the world cultural heritage (Rossi et al., 2020). Many historical buildings and cultural heritage are facing damages caused by both natural events and human activities (Kayan, 2006; Puppio et al., 2023; De Gregorio et al., 2020). Many countries have become increasingly concerned about preserving, promoting and passing on their cultural heritage to new generations. The use of information and communication technologies is recognised as a highly valuable tool in achieving these goals and can be used to promote traditional places (Jara, 2015; Manzhong, 2017), pass on the cultural diversity of a country (Tan, 2016), disseminate traditional symbols specific to the culture of each region (Huang & Chen, 2019), teach traditional music and dances (Ramadijanti et al, 2016), archiving historical buildings in interactive environments (Galantucci & Fatiguso, 2019; Styliadis, 2007; Yılmaz et al., 2007), and digitally preserving intangible cultural heritage (Liu, 2015). Diverse methodologies are used for the generation of three-dimensional models for the preservation of the historical buildings. In the realm of advancing technology, photogrammetry emerges as a highly effective method for documenting historical buildings and facilitating the production of accurate three-dimensional models. The analysis revealed an increased utilization of photogrammetry in historical buildings, particularly after 2016. While 133 of the studies identified in this field were conducted in Italy, 30 studies were conducted in Turkey. However, this number is considered insufficient for the context of Turkey. The bibliometric analysis indicated that the photogrammetric method is commonly linked with 'cultural heritage, laser scanning, and three-dimensional modelling (Figure 1).

This study examined the Hagia Sophia Mosque in Trabzon, which endures to the present day within its significant cultural and historical context. It is aimed to evaluate the transformation process of the building in the light of conservation criteria and to present a digital model of the current state of the building. The applied method involved the utilization of the photogrammetric modeling technique. The most important reason for using photogrammetric modelling method within the scope of the study is that this method is preferred frequently in the international arena, but the use of this

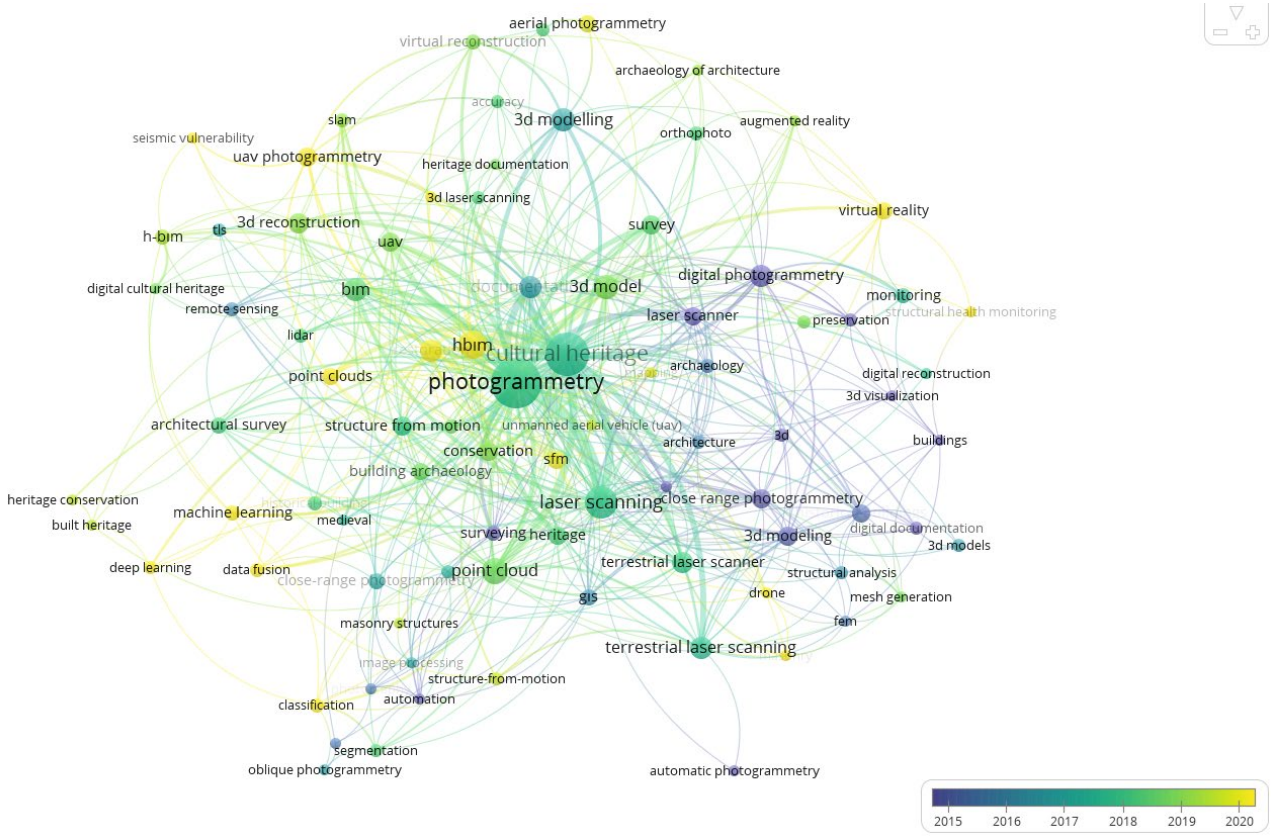

Figure 1 | Bibliometric analysis of the photogrammetry and historical buildings.

method in the field of historical buildings and conservation in Turkey is still insufficient. Firstly, the evolution of Hagia Sophia and its spatial utilization over the years were discussed. Following the presentation of the transformation processes of the building, a digital model of the building was built with the field study carried out in 2023 and the current status of the building was archived. It was determined that the studies on Hagia Sophia Mosque in the literature were discussed in terms of touristic (Demirbulat & Karaman, 2014), cadastral (Çoruhlu & Demir, 2014) and architectural analyses (Aykaç, 2018; Koç, 2020). However, it was noted that no digital documentation study was conducted on its functional transformations. Subsequently, the findings regarding the transformation of the building and the digital modelling of the current situation were evaluated in the context of conservation criteria, and recommendations for the sustainable conservation and documentation of historical buildings were provided. The study can be considered as an effective step in the preservation of the important cultural heritage of the Hagia Sophia Mosque, creating a traceable model and passing it on to future generations.

2. Material and Method

Hagia Sophia Mosque is located in Trabzon, one of the oldest and largest cities on the Black Sea coast in northeastern Turkey. Hagia Sophia is located in a central location and there is the Black Sea Coastal Road to the north. Its proximity to the coastal road makes it easily recognisable by passers-by. Hagia Sophia Mosque, one of the historical elements of the city, has a symbolic feature in terms of the recognition of Trabzon. Today, the building is frequently visited by local and foreign tourists. While in the past, the Hagia Sophia Mosque was surrounded by only a few structures, it is now encircled by residences, shops, and cafes (Figure 2).

The building, exhibiting characteristics from both the Late Byzantine and Seljuk periods, adopts a square-cross plan. At the building's center, the traditional Byzantine dome, supported by four columns, encompasses a high pulley (Kamçır, 2018). There are three apses in three forms, a five-cornered one in the centre and a half-round one on the sides, located on the eastern facade. The side apses were turned into pastophorion cells with two pillars

Figure 2 | The location of the Hagia Sophia.

placed in front of the main apse (Köse, 2000; Köse 2010). The narthex of the west façade, which forms the main entrance of the church, consists of three sections. The sides are covered with a barrel vault and the middle part with a cross vault (Figure 3).

The ornaments of the church are one of its most remarkable features and are the most important identity elements of the building. The church reflects an important design with its porticoed entrances on the west, north and south sides (Ahunbay, 2018; Antony, 2016). Even though it has been damaged today, the apses, dome, dome transitions, walls, entrances and the narthex are all covered with frescoes. According to D. Talbot Rice, the frescoes reflect the "Byzantine Renaissance" of the late 13th or early 14th century (Rice 1997). The study, unraveling the metamorphosis of the Hagia Sophia Mosque and offering digital insights into its current state, was structured across four stages. The initial stage involves information gathering, followed by field studies in the second stage, transformation analysis and photogrammetric modeling in the third stage, and evaluation with recommendations in the fourth stage (Figure 4).

In the first stage, a systematic literature review was conducted. Two qualitative research methods were used at this stage. Data collection and tracing methods were utilised while creating research and theoretical background components. Data collection method is a research technique used to obtain information that will lead to the conclusion of the research subject (Symon & Cassell, 1998: Yıldırım, 1999). The tracing method or process tracing method is a qualitative research method in which the causal conditions of a situation are examined by including the process (Bennett & Elman, 2006). At this stage, the history of the building was determined and information about the historical features and transformations it has experienced from past to present was collected. The second stage involves a field study wherein the current status of the building, its physical characteristics, and its relationship with the city were investigated through on-site observations. Field studies provide the opportunity to understand and analyse events, objects or actors by observing them first-hand as well as collecting information (Aydın, 2018). With the visits to Trabzon in 2023, the building was investigated on site and visual and technical information was provided. In this process, aerial photography method was used to obtain the visuals needed to document the current condition of the building.

The third stage of the study consists of two steps. The first step involved a systematic presentation of the building's transformation based on data obtained from the first and second stages. The current use of the building was analysed, and the interventions made during its transformation were presented. The photogrammetric modeling technique was used to generate a digital three-dimensional model of the building in the second step. A digital model is a computer-represented version of real-world objects or systems and can be produced using various techniques (Evens & Hauttekeete, 2011; Gomes et al., 2014). The study utilized a digital photogrammetric model to create a three-dimensional geometric representation of an object through the analysis of photographic images and measurements. This process is typically executed through software algorithms, which employ depth perception algorithms to generate a measured model from photographs. During the fourth stage of the study, the transformations of Hagia Sophia were discussed according to international preservation criteria and the evaluation of the digital model that could be passed on to future generations was included. The advantages and limitations of the model created for the Hagia Sophia Mosque were mentioned at this stage.

Figure 3 | Plans, views and sections of the building and visuals from the exterior.

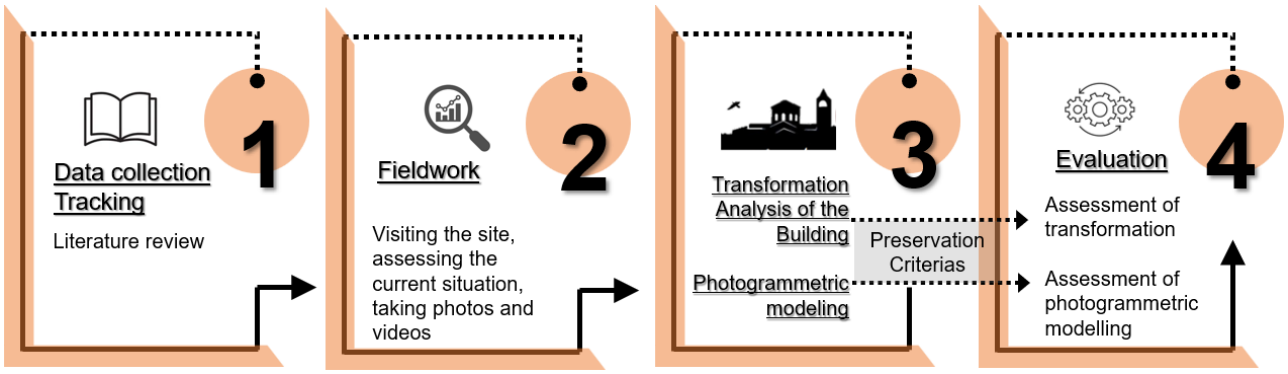

Figure 4 | The diagram of the stages of the study..

3. Findings

3.1 Transformation Processes of Hagia Sophia's Cultural Heritage

The church was built by Manuel I Komnenos between 1238 and 1263 (Mango 2006). According to Evliya Çelebi, the building was converted into a mosque in 1577 and used as a mosque for a long time. It was restored in 1864 with the help of Rıza Efendi. The bell tower, located 25 meters west of the museum, was built in 1427 (Demirbulat & Karaman, 2014; Köse, 2013). The building served as a warehouse and hospital during the Russian occupation from 1916 to 1917. In 1958-1962, the University of Edinburgh restored the building, and the Directorate of Foundations cleaned and revealed all of its frescoes (Figure 5) (Koç, 2020; Köse 2012).

The preservation of the frescoes in the restoration of the Hagia Sophia mosque was the primary goal of the long-term restoration work. The restoration was based on the principle of minimum intervention. plexiglass lighting system was used to avoid damaging the frescoes inside the mosque. This allowed visitors to view the frescoes during worship by turning off the lighting system. The historical value of the current facades and interiors can be realised by exploring the plan and views of the building (Figure 6).

3.2 Creating a Digital Inventory of the Hagia Sophia Mosque

Documenting historical buildings is crucial for conservation practices as they contain significant cultural and social data. This study created a digital three-dimensional photogrammetric model of the Hagia Sophia structure in Trabzon, which is an important reflection of architectural

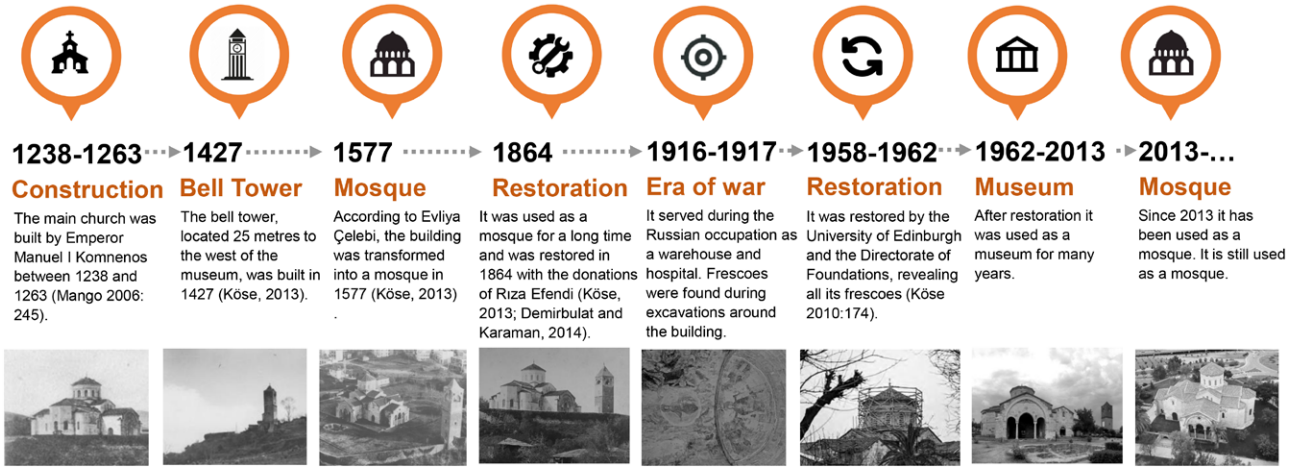

Figure 5 | Hagia Sophia timeline.

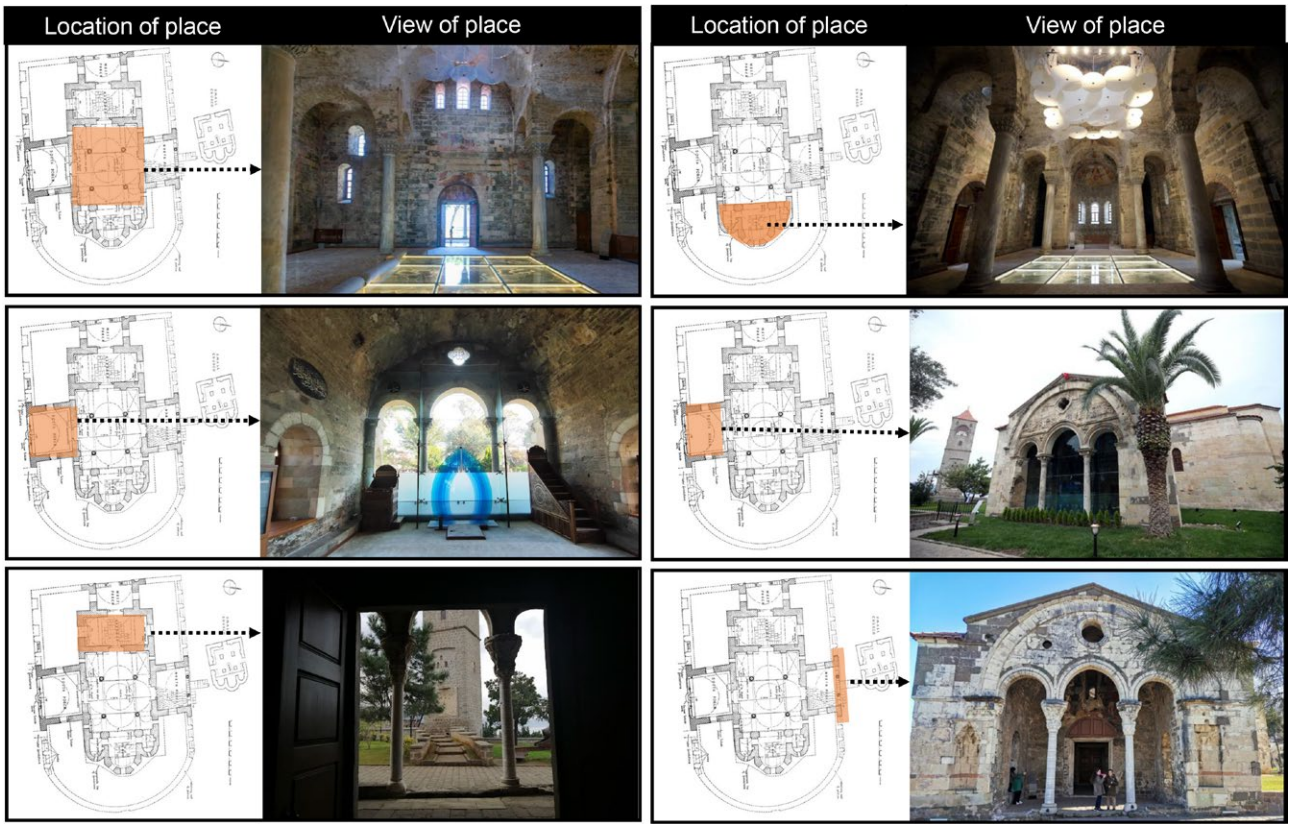

Figure 6 | Images of the current status of Hagia Sophia.

culture and material use in Trabzon. To create a photogrammetric model, a series of photographs must be taken to enable the depth perception algorithm to function effectively. It is crucial that these photographs are related and mutually identifiable. It is recommended that each photo frame contains approximately 30% of the same content as the previous frame. This criterion enables the software to align photos with each other and create a comprehensive model. This process is essential for obtaining reliable and accurate results in photogrammetry applications.

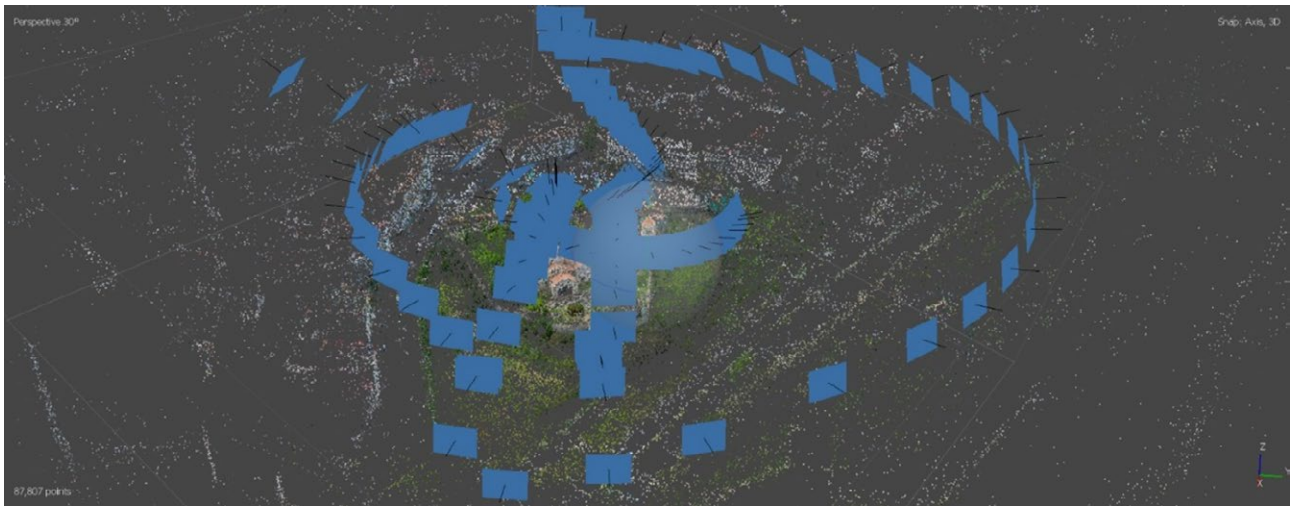

Figure 7 | Trabzon Hagia Sophia – Camera angles and point cloud model.

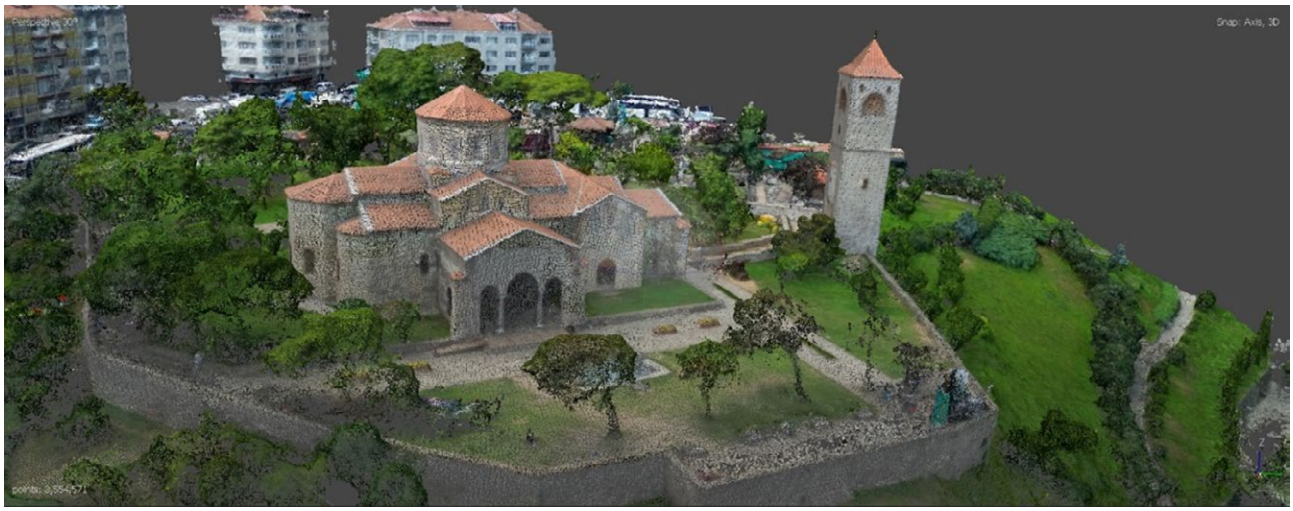

Figure 8 | Trabzon Hagia Sophia – Dense point cloud model.

The photographs were taken as part of the fieldwork carried out in 2023 for the Trabzon Hagia Sophia. The photogrammetric model was built using the Metashape software (Agisoft, 2023). The first step of the model creation process is to add 101 photographs obtained during the field studies to the Metashape. These photos were used for the program's alignment process and formed the basis of the model. During the alignment process, Metashape aligned the added photos based on overlapping points. This resulted in the creation of a point cloud model that contains the structure, consisting of 87,807 points. This process revealed the camera angles of the photo frames aligned by the software (Figure 7).

The process of creating a dense point cloud began after aligning the photographs. This was achieved using the Metashape program's automatically defined 'build dense cloud' command (Figure 8). The dense point cloud of the building contains a total of 3,554,571 points. Before generating the mesh model from the dense point cloud, it is possible to quickly clean up unnecessary points. The program's quick selection command can be used to perform the cleaning process. This allows for the selection and removal of data that enters the photo angles but is not necessary for model creation. Unnecessary elements, such as structures that are far from the main structure, trees, cars, and roads, can be cleared from the program

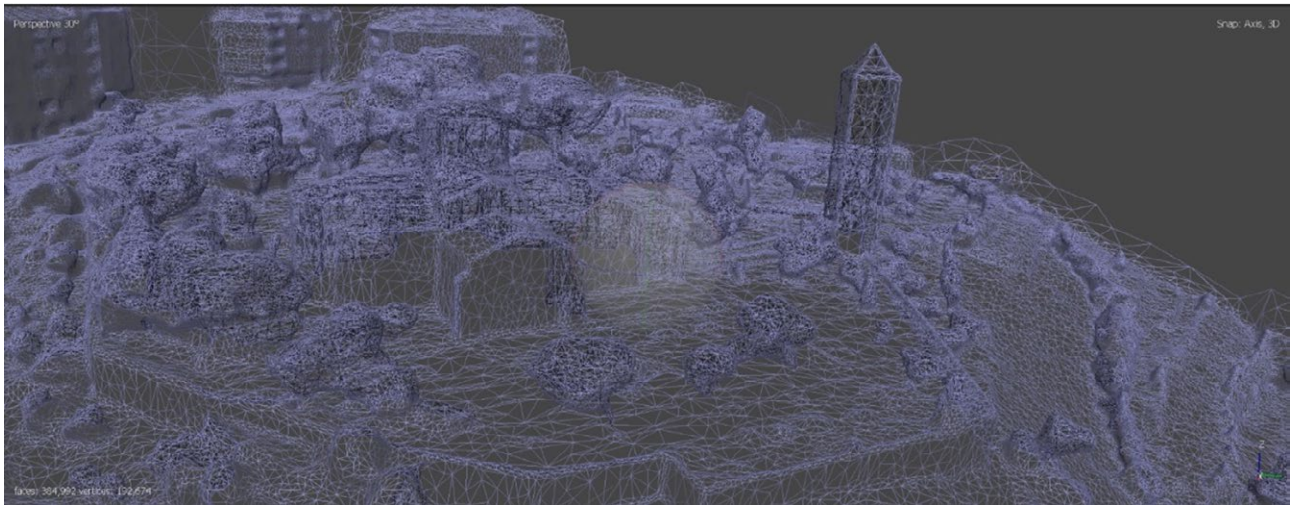

Figure 9 | Trabzon Hagia Sophia – Mesh model.

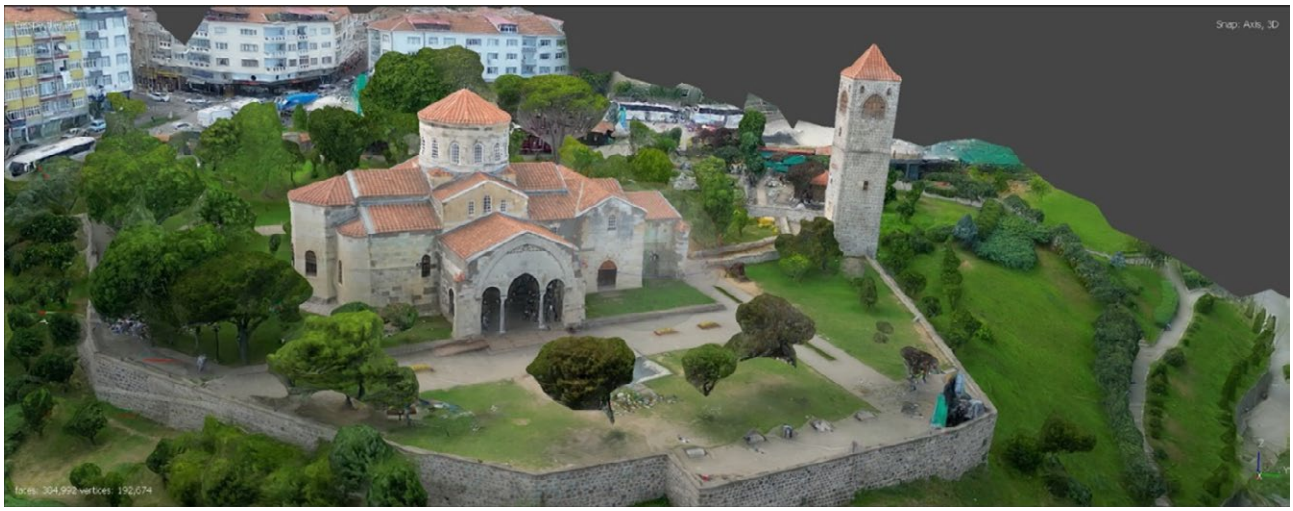

Figure 10 | Trabzon Hagia Sofia – Three dimensional measured model.

interface. Performing the cleaning process is crucial for a faster and more accurate mesh generation. Cleaning may be performed to reduce model generation time.

The mesh model was built by meshing with the dense point cloud. Therefore, removing unnecessary data in the previous step shortens the process. After a quick cleaning process on the dense point cloud for Hagia Sophia, the mesh model was generated (Figure 9). The model was based on the mesh number 384,992.

After the mesh model was complete, the textures in the photographs can be mapped onto the mesh model. This can be performed using the software's automatic texture recognition command. In the Hagia Sophia example, once the mesh model was complete, the textures from the photographs were transferred to the model. The result of this stage was a measured model reflecting the current state of the building (Figure 10).

The model produced as part of the study provides data that is quite compatible with the actual dimensions of the structure of Trabzon Hagia Sophia. The model represents a digital record of Hagia Sophia according to 2023 data and creates an archive that contributes to intergenerational dialogue. The software can also provide access to the numerical data of the photogrammetric model generated from the aerial photographs (Table 1).

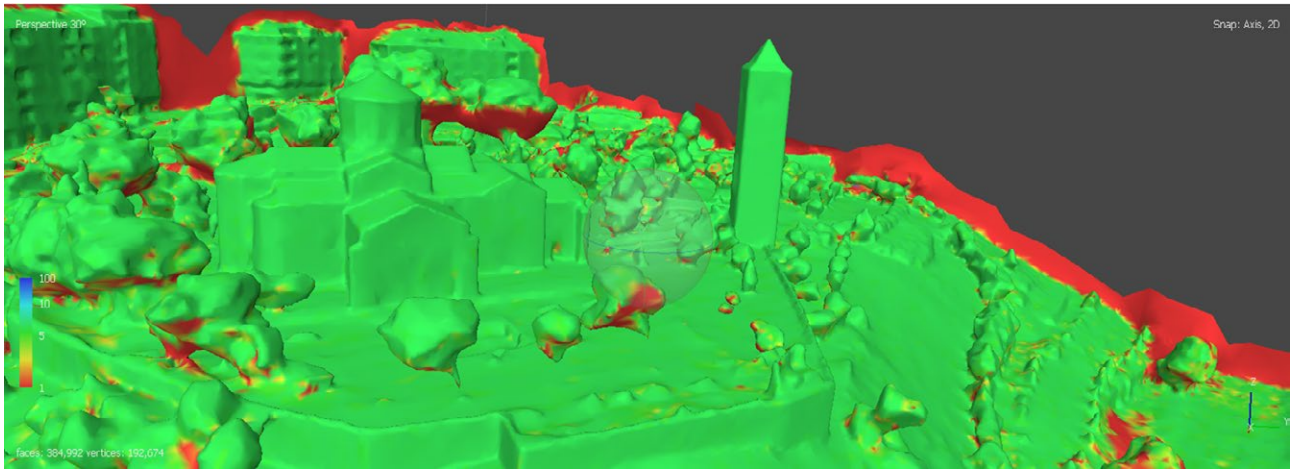

Figure 11 | Trabzon Hagia Sophia – Confidence in the model.

Table 1 | The numerical data of Trabzon Hagia Sofia's model.

Model Type	Numerical Data
Point Cloud Model	87,807 points
Dense Cloud Model	3,554,571 points
Mesh Model	384,992 faces
Mesh Model	192,674 vertices

When the model was finalised and the numerical data were presented, defective or missing points of the networks can be checked on the model. The regions in green represent the regions where the meshes are accurate and complete, and the regions in red represent the regions where the meshes are defective. In the study focused on the Hagia Sophia structure, it can be concluded that the model of the entire structure is formed in green, which means that the model can be created completely (Figure 11).

4. Discussion of Results

Preserving historical and cultural heritage is one of the best ways to enhance a society's connection to its past, present and future. Identifying the past and present of cultural heritage through its preservation is one of the most important requirements for sustainable conservation in order to understand the past and provide meaning to the present. The evaluations of the study, which reveal the transformation process of Trabzon Hagia Sophia Mosque from the past to the present in the traces of cultural heritage and the digital perspectives of its current situation, were discussed in two parts according to the findings obtained. When the findings regarding the transformation of Trabzon Hagia Sophia Mosque were evaluated:

- One of the most defining characteristics of historical buildings is their spatial organisation. The spatial organisation is the most significant indicator that should be taken into consideration when assigning a new function. Therefore, the ICOMOS (1999) Traditional Architectural Heritage Regulation states that new uses of traditional buildings should respect the spatial integrity, character and form of the building, thus emphasising the importance of spatial organisation. At this point, although the Hagia Sophia Mosque has been used for various functions over the years, it is considered a positive approach in terms of sustainable conservation that there has been no major change in the spatial organisation of the building from the past to the present.

- Another contemporary approach applied in the reuse process is the space created by enclosing the south facade of the building with glass. ICOMOS (2003) stated that any intervention in historical buildings should, as far as possible, respect the original design, construction technique and historical value of the structure and preserve traces that will enable it to be understood in the future. The ICOMOS (1999a) also emphasised that new elements or parts should be identifiable from the old materials. Evaluated against these principles, it can be said that the use of glass in the Hagia Sophia Mosque does not hide its historical texture. On the contrary, it seems that a positive approach has been taken in terms of distinguishing from the historical texture and highlighting the original texture.

- Article 15 of the ICOMOS (1999a) Burra Charter highlighted that interventions to a building must be reversible and temporary. From this perspective,

when the interventions at the Hagia Sophia Mosque were examined, it was found that they were largely recyclable, and this was considered to be a sustainable approach to conservation.

- The reuse of the building as a mosque required some changes and interventions. The most notable of these were the frescoes that remained on the interior of the building from its original function as a church. To prevent these frescoes from being seen during the mosque's function, the plexiglass used on the ceiling allowed the frescoes to be covered during services and also allowed visitors to see by turning off the lights when required. This approach can be also considered to be compatible with contemporary conservation approaches, as it also supports the use of the building for tourist purposes.

- Article 11 of the ICOMOS (1999a) Burra Charter highlighted that the areas and objects around the historical site should contribute to the cultural value of the building. In this context, functions such as cafes, schools, offices, etc. located in the immediate surroundings of the Hagia Sophia Mosque contribute to the attractiveness of the building as a tourist destination.

The use of digital technologies in the documentation of historical and cultural heritage is a necessity of the age and an approach that provides faster and more effective results. The study includes assessments of digital modelling techniques and digital perspectives of the current situation of the Hagia Sophia Mosque:

- The study produced a digital model of the Hagia Sophia Mosque. The production of models of the building at specific times in the future provides an environment that allows the building to be traced between its past and future. At this point, the use of digital modelling in documentation is stated in Article 4 of the ICOMOS Charter for the Protection and Management of the Archaeological Heritage (1990), inventory preparation should be considered as a continuous and dynamic process. It will be beneficial to monitor the dynamic and variable process mentioned in this principle. This will make it easier to document and follow the changes and transformations that the building has undergone over the years

- ICOMOS (2017) Principles for the Conservation of Wooden Built Heritage emphasises the importance of collecting and securely documenting all documents relating to each part of the structure, as well as information on traditional craftsmanship skills and techniques. Digital modelling allows complex geometric measurements of historical buildings to be clearly obtained. Considering that the documentation and evaluation of tall structures requires long and difficult measurements, it is advantageous to use photogrammetric methods instead of traditional techniques. In addition, photogrammetric methods can provide textural data of the building. As these data are obtained from the building's own visuals, more realistic models are presented. At this point, digital modelling techniques provide results that closely resemble the actual appearance and facilitate the user's perception of the structure.

- Similarly, Article 1 of the ICOMOS (1999c) Principles for the Protection of Historic Timber Structures states that "All pertinent documentation, including characteristic samples of redundant materials or members removed from the structure, and information about relevant traditional skills and technologies, should be collected, catalogued, securely stored and made accessible as appropriate". The digital modeling method offers an additional advantage through its capacity to effortlessly measure intricate components of buildings and produce a three-dimensional model. Notably, the photogrammetric modeling of architecturally detailed, embroidered, decorated, and ornamented elements—challenging to measure manually using traditional methods—can be accomplished in a more straightforward and practical manner.

- ICOMOS (2017) Principles for the Conservation of Wooden Built Heritage refers to the requirement for inventory records and documents to be accessible as deemed appropriate. At this point, digital methods can be said to facilitate the accessibility of information and provide a practical process compared to traditional methods.

- In Article 11 of the Principles for the Conservation of Industrial Heritage Sites, Structures, Areas, and Landscapes by ICOMOS (2011), it is emphasized the importance of documenting the changes that a building has undergone over time. Similarly, the ICOMOS (1999a) states that changes made over time should be respected and considered as a document reflecting the characteristics of traditional architecture. In this context, the digital inventory production process offers an efficient, updatable, and shareable platform, facilitating easy intervention and documentation of changes.

- The study obtained images of the entire building using unmanned aerial vehicles during the photogrammetric modelling process. This allowed for a more holistic approach to the massing of the building. It can be said that the statement under the heading of research in Article 5 of the ICOMOS Charter for the

> Protection and Management of the Archaeological Heritage (1990), states, "Such investigation embraces the whole range of methods from nondestructive techniques through sampling to total excavation."

Digital modeling techniques not only contribute to assessing the current condition of historic buildings but also establish a foundation for conservation projects. Consequently, they enhance the practicality of survey projects in terms of both information accuracy and time efficiency. In this study, the photogrammetric method is employed to model the external surfaces of the Hagia Sophia Mosque, demonstrating its adaptability for modeling both interior and exterior surfaces.

While photogrammetric modeling and the creation of three-dimensional digital models of historical buildings offer numerous advantages, this modeling technique also has its limitations and constraints. One of the primary limitations in the photogrammetric modeling of historical buildings is the accessibility to the structure. Many historical buildings have complex geometries, ornate architectural features, and restricted access areas, which can impede the collection of comprehensive image data required for accurate 3D modeling. Capturing sufficient images from all necessary angles and positions can be challenging, particularly in confined spaces or at high elevations. Furthermore, the varying conditions of historical buildings, such as weathering, deterioration, or the presence of obstructions, can affect the quality and accuracy of the photogrammetric data. Factors like uneven lighting, shadows, and reflective surfaces can introduce errors and distortions in the resulting 3D model.

The resolution and detail level of the 3D model are also constrained by the image resolution and the capabilities of the photogrammetric software. Highly intricate architectural features, small-scale elements, and delicate details may not be adequately captured or represented in the final 3D model, limiting its usefulness for comprehensive documentation and analysis. Additionally, the post-processing and data integration steps required for photogrammetric modeling can be time-consuming and labor-intensive, particularly for large-scale historical structures. The need for integrating various data sources and software can further complexify the process.

5. Conclusion

The cultural heritage of a society serves as a bridge connecting its past, present, and future. One of the most effective means to fortify the relationship between a society and its temporal continuum is to preserve its historical and cultural heritage. Therefore, one of humanity's paramount responsibilities is to safeguard this heritage, assess its current state, document it, and restore it to its original condition. This ensures the accurate transmission of historical heritage to future generations. One of the most fundamental requirements of sustainable conservation is that interventions in the restoration and reuse process of the building must be conducted in accordance with international conservation criteria. Furthermore, it is essential to document all changes and transformations that the building experiences. Based on this, the transformation process of the Hagia Sophia Mosque in Trabzon was evaluated in the context of international conservation criteria and the digital model of its current situation was presented. The study has provided the first step towards a digital environment where the building can be monitored for its past, present and future. It is crucial that this building, which represents the cultural and social heritage of its region, is passed on to future generations in its original state.

Digital approaches to documentation have increased the diversity of techniques used to document cultural heritage. Digital modelling is a technique that needs to be adapted to the process of recording historical artefacts. Depending on the area, digital modelling can be faster, cheaper and more accurate. It may also be preferable in terms of visualisation and sensitivity. These advantages indicate that photogrammetry can provide a modern and dynamic environment for the documentation of cultural heritage. While the digital model produced in this study provides an accurate documentation of the building, it also contributes to possible restoration and conservation works. Furthermore, it will allow the building to be promoted through tourism activities by providing digital models to users.

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