Virtual Archaeology Review, **17**(35): 25621, 2026
https://doi.org/10.4995/var.2024.25621

Received: February 10, 2026
Accepted: May 26, 2026

OPTIMISATION OF 3D MODELS FOR ARTWORKS FROM THE CATHEDRAL OF SANTIAGO DE COMPOSTELA MUSEUM

OPTIMIZACIÓN DE MODELOS 3D DE OBRAS DE ARTE DEL MUSEO DE LA CATEDRAL DE SANTIAGO DE COMPOSTELA

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Highlights:

- The optimised models reduced graphics memory usage by up to 75% and increased frame rate per second in engines such as Unreal Engine 5, making them easier to display in mobile applications and virtual environments.
- Visual comparisons in Sketchfab and Unreal Engine 5 revealed no visually significant differences between the photogrammetric model and the optimised model at typical viewing distances.
- Retopology is essential for enabling the digital dissemination of cultural heritage and balancing visual quality and technical efficiency.

Abstract:

The digitisation of cultural heritage through photogrammetry has transformed the preservation and dissemination of artworks. However, this technique can produce three-dimensional (3D) models with excessively complex geometry, making them inefficient for real-time applications in virtual reality (VR), on mobile platforms, and in web-based viewers. This limitation restricts access to digital heritage, particularly for users with limited hardware and those in regions with technological restrictions. To address this limitation, this study explores optimisation through retopology, using three 3D software tools, such as Instant Meshes, Blender, and ZBrush. These tools were selected because of their ability to reduce the number of polygons without a significant loss of detail. Their effectiveness was subsequently evaluated through a comparative analysis. The study focuses on the optimisation of 3D models of artworks from the Cathedral Museum of Santiago de Compostela: Santiago Crowned, David, and Christ in Majesty. A mixed-methods approach is used to evaluate reductions in mesh size and polygon count, as well as rendering performance, across the different optimisation workflows. The results identified Instant Meshes as the best-performing tool, as it achieves an effective balance between automation and geometric preservation. Blender ranked second, as it offers more precise control for complex models. Moreover, none of the optimised models showed visual degradation on web platforms such as Sketchfab or in Unreal Engine 5, which ensured visual authenticity and compatibility with mobile devices. Finally, this research highlights the role of 3D optimisation in democratising access to cultural heritage by enabling the creation of lightweight and high-quality digital replicas that institutions can use to disseminate art globally, support education, and safeguard artworks.

Keywords: 3D model optimisation; digital cultural heritage; cultural heritage dissemination; documentation; 3D reconstruction

Resumen:

La digitalización del patrimonio cultural mediante fotogrametría ha transformado la preservación y difusión de las obras de arte. Sin embargo, esta técnica plantea desafíos como la geometría excesiva en los modelos tridimensionales (3D) resultantes, lo que los hace ineficientes para aplicaciones en tiempo real de realidad virtual (RV), plataformas móviles o visores web. Esta limitación dificulta el acceso al patrimonio digital, en particular para los usuarios con hardware limitado o residentes en regiones con restricciones tecnológicas. Para abordar esta limitación, este estudio explora la optimización mediante la retopología, que se implementó utilizando tres herramientas de software 3D: Instant Meshes, Blender y ZBrush, debido a su capacidad de reducir el número de polígonos sin una pérdida significativa de detalles para realizar posteriormente un análisis comparativo que evalúe su eficacia. Este estudio se centra en la optimización de obras de arte del Museo de la Catedral de Santiago de Compostela llamadas Santiago Coronado, David y Cristo en Majestad. Se utiliza un enfoque de métodos mixtos que incluye la evaluación de la reducción del peso de la malla, el número de polígonos y el rendimiento del renderizado en diferentes flujos de trabajo de optimización. Los resultados identificaron Instant Meshes como la herramienta de mayor rendimiento, puesto que logra un equilibrio óptimo entre automatización y preservación geométrica. Blender ocupó el segundo lugar, ya que ofrece un control más preciso en el procesamiento de modelos complejos. Ninguno de los modelos optimizados mostró una degradación visual perceptible en plataformas web como

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Sketchfab y en Unreal Engine 5, lo que garantizó la autenticidad visual y la compatibilidad en dispositivos móviles. Además, esta investigación destaca el papel de la optimización 3D en la democratización del acceso al patrimonio cultural porque permitió crear réplicas digitales ligeras y de alta calidad que las instituciones pueden utilizar para difundir el arte a escala global, apoyar la educación y salvaguardar obras artísticas.

Palabras clave: optimización de modelos 3D; patrimonio cultural digital; difusión de patrimonio cultural; documentación; reconstrucción 3D

1. Introduction

Health, social, and political–economic crises often present significant international socioeconomic challenges, as observed during the recent global pandemic, which had a profound impact on culture. Galleries and museums closed their doors and restricted public access, leading to a decline in visits with economic repercussions for their revenues and social implications for their mission to educate and transmit culture to society (Agostino et al., 2020). In 2020, owing to the pandemic, the cultural sector, in particular, faced one of the most challenging obstacles following border closures and the indefinite suspension of services (Cicerchia & Solima, 2021).

In response to this new landscape, various cultural sites reinvented themselves and began to use new technologies for the dissemination of cultural heritage, seeking a presence on social media through videos, photographs, and 3D models obtained through photogrammetry. Photogrammetry is capable of obtaining reliable information to accurately study and define the shape, dimensions, and position of any object in space (Instituto Geográfico Nacional, 2024; Kasapakis et al., 2024).

Currently, 3D scanners are also becoming a standard source of data input in various application areas. However, image-based modelling remains the most comprehensive, cost-effective, portable, flexible, and widely used approach, suggesting that image-based 3D modelling could be an excellent and suitable method for recording, documenting, and visualising excavated archaeological heritage (Remondino & El-Hakim, 2006).

Therefore, technological advancements facilitate the generation of increasingly accurate 3D models through photogrammetric techniques, especially for those without deep knowledge of these techniques. Additionally, improvements in computer hardware reduce the processing time of 3D models, highlighting significant technological evolution and providing public access to the internet via computers or mobile devices (Apollonio et al., 2021).

Consequently, the significance of using photogrammetry in museums to create 3D models of exhibited artworks lies in the preservation of cultural and archaeological heritage and the integration of interactive educational resources to enrich the visual experience of visitors (Hassani, 2015; Liritzis et al., 2021; Florescu et al., 2022).

Thus, 3D models represent an attractive proposition for museums as, in the event of any crisis, their low cost and accessibility can enable the use of mobile applications from the comfort of home and within museums through mobile augmented reality. Additionally, 3D models contribute to wider dissemination by providing access to collections of artworks that, combined with internet use, offer accessibility to the population regardless of their geographical location, with the aim of spreading knowledge, culture, and history (Wang & Zhu, 2022; Cruz Franco et al., 2022). This technological advancement allows museums and galleries to present new digital proposals and even entirely virtual cultural events (Shlyakhetko & Greguš, 2024).

Therefore, enhancing artworks through 3D models using photogrammetry generates the possibility of creating visually suggestive virtual environments, as their simultaneous use of 3D models and their exact representation delights and satisfies the public, as seen in the case of the Temple of Baalshamin in Palmyra. Between 2015 and 2017, Palmyra suffered damage because of armed conflicts. Historical monuments such as the Temple of Baalshamin did not survive the devastation that ensued, making the efforts to document and preserve Palmyra's heritage and its reconstruction in 3D crucial.

Therefore, the use of 3D pieces has a broader global reach through cutting-edge tools, aiding in their conservation, preservation, and dissemination (Anton et al., 2018).

The 3D models served as educational and learning tools because they allowed visualisation of these sites as they were before the destruction (Bobou et al., 2020).

Another example occurred in 2018 at the National Museum of Brazil, which suffered a fire caused by an electrical short circuit. This incident resulted in the loss of priceless works of art. This situation could have taken advantage of photogrammetry had it been used before the fire, because it could have helped preserve the pieces destroyed in the incident (Puspita et al., 2021), which were housed in the museum (Araujo, 2019).

Since having partially or fully virtualised pieces from the collections would have made restoration more efficient because the virtualised objects could have been useful for their destroyed physical counterparts (Acke et al., 2021).

The 2019 fire at Notre-Dame de Paris further underscored the vulnerability of heritage assets to catastrophic events (Ferreira, 2019). It also intensified public debate about the value of digital surrogates for heritage communication and education.

In this context, commercial and cultural digital experiences such as high-fidelity virtual replicas created for entertainment were frequently cited as examples of how detailed 3D assets can broaden public engagement. However, regardless of their documentary status, such assets face a practical limitation for dissemination: photogrammetric-grade geometry typically requires optimisation to be usable on resource-constrained platforms.

Therefore, this study addresses the following research question: Why is the optimisation of 3D photogrammetric models in museums recommended? Since the advancement of visual technologies generates alternatives that, combined with art, allow the creation of highly detailed elements used in virtual reality (VR) which can lead to a better experience for the visitor or allow a better understanding of the work of art (Bachiller et al., 2023), the objective of this research article is to determine the appropriate way to optimise 3D photogrammetric models for museums, with the goal of contributing to the reader's understanding of how to optimise 3D parts obtained by photogrammetry so that they consume fewer graphic resources and can be disseminated at scale on mobile applications.

In addition, the following research is qualitative because the fidelity of 3D scanning performance and results are determined through the optimisation of 3D photogrammetry (Dixit et al., 2019; Morgan, 2022). This research work is structured in six sections: the first is the introductory section; the second is the methodological section; the third section facilitates the understanding of photogrammetric model optimisation; the fourth section focuses on texture projection; the fifth section addresses the rendering of the original and optimised models; and the sixth section focuses on 3D model visualisation. The research concludes with the results and discussion, and finally, the conclusions.

2. Methodology

The methodology employed in this study combines photogrammetry techniques, digital model optimisation, and comparative evaluation, adopting a mixed-methods approach that incorporates both qualitative and quantitative data. The qualitative assessment evaluates the visual appearance of the resulting models against that of their original counterparts, whereas the quantitative analysis examines both the reduction in the file size of optimised 3D models and improvements in the rendering times. The workflow follows four sequential stages: 1) data acquisition; 2) photogrammetric processing; 3) model optimisation and 4) validation and performance evaluation (Fig. 1).

For the digitisation of the artistic pieces (Christ in Majesty, Santiago Crowned, and David) from the Museum of the Cathedral of Santiago de Compostela, an OM10 Mark III camera with a 50 mm lens was used, with an aperture of f/5.6 and an exposure time of 1/250 s. The images were captured in RAW format under controlled lighting conditions, using ring light and a rotating platform. This approach allowed the loss of information in shadow or overexposed areas to be minimised (Bobkowska et al., 2021), ensuring the quality of the input data for photogrammetric processing.

The image processing was performed in Adobe Lightroom v. 6.0 for basic exposure and white balance adjustments. Agisoft Metashape v.1.7.0 was subsequently used for its precision in close-range photogrammetry (Verykokou et al., 2021), to generate 3D models through the construction of dense point clouds, polygonal meshes, and textures.

3D photogrammetry is understood as the science that measures the exact position of an object's surface points by collecting data from multiple photographs, allowing for the rapid and accurate reproduction of physical elements. When applied to cultural heritage, this technique is considered reliable for obtaining the shape, texture, colour, quality, and unique details of objects (Dhanda et al., 2019; Kasapakis et al., 2024).

It is important to recognise that 3D models created using photogrammetry are not ideal for integration into graphics engines because of their large size in megabytes (MB) (Inzerillo et al., 2020).

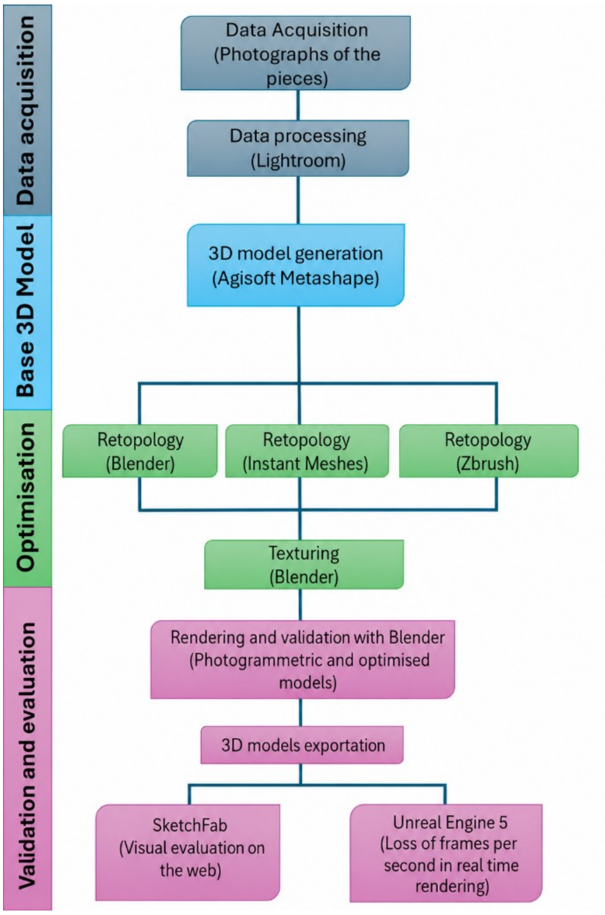


Figure 1: The comprehensive workflow of this study is presented from top-to-bottom and consists of four interconnected stages: 1) data acquisition; 2) photogrammetric model generation; 3) optimisation; and 4) validation and evaluation.

In this way, both the 3D model and its colour map are exported in FBX format for optimisation through a mesh reconstruction process called 3D retopology (Gonizzi Barsanti et al., 2022).

Therefore, the next step involves optimisation, which consists of reconstructing the mesh through a retopology process to reduce its size while preserving the original shape of the 3D photogrammetric model. This ensures compatibility with other software and facilitates its integration with various 3D design applications (Munkberg et al., 2022; Perticarini et al., 2020).

Furthermore, optimising 3D models achieves greater fluidity without sacrificing the aesthetic quality of artistic works (Obradović et al., 2020).

The optimisation stage of the 3D models implemented three different approaches in mesh reconstruction: 1) Instant Meshes v. 2.1 through an automatic process; 2) a semimanual process in ZBrush v. 2022.0.6; and 3) Blender v. 3.5 with a completely manual process. These were compared by the time it took to perform the retopology process in each of them.

The use of retopology not only facilitates more efficient model management but also allows for the creation of a UV coordinates (texture space) where U and V denote the two-dimensional axes that textures the models and accurately represents them with respect to the original object (Villanueva, 2022). In this way, a 3D model becomes two-dimensional, with X (U) and Y (V) coordinates, also allowing for the acquisition of colour, texture, and roughness information from other models (Lupiani, 2025).

Therefore, the new optimised 3D models resulting from the optimisation process lack texture; the generation of UV maps allows information to be transferred from the photogrammetrically generated part to the simplified 3D models obtained by retopology through a texture projection process, thus preserving the original appearance of the photogrammetric model in the optimised 3D piece (Knodt et al., 2023; Chen et al 2022).

After performing texture projection in Blender and acquiring the different maps from the photogrammetric models, tests were conducted with different graphics cards on the optimised 3D models versus their counterparts, measuring the rendering times and the amount of graphics resources required by each of the rendered 3D models in Blender. The graphics cards used were: Nvidia GTX 1060; Nvidia RTX 2070 Super; and Nvidia RTX 3070 Ti.

The 3D models with their different materials were subsequently exported to two different 3D viewers: 1) Sketchfab (a web-based platform) and 2) Unreal Engine 5 (UE5), with the purpose of evaluating the performance of the 3D models, both in a web viewer and in a real-time rendering engine.

To quantitatively assess the geometric fidelity of the optimised models, a comparison between the original photogrammetric 3D models and the optimised models was performed using CloudCompare (Dewez et al., 2016). The cloud-to-mesh (C2M) distance was calculated to measure the maximum and mean deviation between the two surfaces. Additionally, the root mean square error (RMSE) was computed to provide a global measure of geometric discrepancy. Colour-coded heatmaps were generated to visualise the spatial distribution of errors across each model's surface.

3. Case Study: The Cathedral Museum of Santiago de Compostela

The Museum of the Cathedral of Santiago de Compostela, located in the city of the same name in Galicia, Spain, was created in 1930 to compile and preserve the history of the sanctuary because of the social, political, economic and religious importance of the location of the tomb of the Apostle Santiago (Salvat, 1981). The site has been part of the UNESCO World Heritage list since 1985, receiving thousands of pilgrims annually. The museum houses a significant collection of artistic and archaeological pieces dating from Roman times to the present day (González & Medina, 2023).

For this study, three artworks from the museum's collection were selected: Santiago Crowned, Christ in Majesty, and David, Figure 2. These pieces were chosen because of their complex geometry, varied materials, and high level of detail, making them suitable for evaluating the effectiveness of different retopology techniques.

(a) (b) (c)

Figure 2: Original artworks from the Cathedral Museum: a) Santiago Crowned; b) Christ in Majesty; and c) David.

4. Optimisation of 3D photogrammetric models

Photogrammetric 3D models, often referred to as high polygon (HP) models, are characterised by a high level of geometric detail that faithfully captures the physical appearance of cultural heritage objects. However, their high polygon count results in large file sizes and significant computational demands, making them difficult to manipulate, visualise, and export to real-time applications such as web viewers, mobile platforms, or virtual reality environments (Caradonna et al., 2018).

To address this limitation, optimisation techniques such as retopology are employed to generate low-polygon (LP) models that retain the essential shape of the original object. Through texture projection, visual details including colour, normals, ambient occlusion, and roughness are transferred from the HP model onto the LP model (Rechichi & Fiorillo, 2019; Knodt et al., 2023). This process preserves the visual authenticity of the original piece while drastically reducing the polygon count and file size, enabling efficient rendering and smooth performance in graphics engines and interactive applications.

In the context of cultural heritage, such optimisation is essential for ensuring that digital replicas can be disseminated across a wide range of devices, including those with limited hardware capabilities. By balancing visual quality with technical efficiency, optimised models facilitate broader public engagement through virtual exhibitions, educational tools, and immersive experiences (Obradović et al., 2020; DaCosta & Kinsell, 2023).

5. Texture baking

When optimised 3D models lack textures, unlike the original Agisoft Metashape models, it becomes necessary for them to acquire the same visual appearance through a texture projection process (Verhoeven, 2017).

Agisoft Metashape, while suitable for generating high-polygon photogrammetric models, does not support texture baking between models of different topologies. For this reason, Blender was selected because it provides dedicated tools for UV mapping, texture projection, and baking of multiple material maps (colour, normal, ambient occlusion, roughness) using its Cycles rendering engine (Chai & Li, 2022; Astuti et al., 2022; Knodt et al., 2023).

Therefore, the next step requires that the geometries of the two 3D models occupy the same virtual space in Blender. This requires aligning the two models as closely as possible, ensuring that the optimised 3D model is placed on top of the original part so that the faces of the optimised model acquire information from the original model through the texture projection process; the resulting information should include colour maps, normals, ambient occlusion maps and roughness maps (Chai & Li, 2022).

6. Rendering

After the projection of textures, different graphics cards were subsequently used to test the speed and amount of video memory required to generate a render from the optimised 3D models, since rendering is the process by which 2D images are created from 3D models for visualisation.

The video graphics card benchmarking tests aimed to establish an optimal balance between visual quality and performance. This comparison measured the rendering time of the photogrammetric 3D model versus the optimised 3D model, prioritising high-fidelity 3D output images with minimal computational cost and the least possible quality degradation.

The performance evaluation criteria included the rendering time, video memory (VRAM) utilisation, and output image fidelity. A comparison was conducted to quantify the trade-offs between computational efficiency and visual precision. Notably, effective 3D model optimisation proved critical for scalable dissemination across resource-constrained platforms, such as mobile devices and VR headsets, where hardware limitations demand a stringent balance between polygonal complexity, texture resolution, and real-time renderability.

7. 3D model visualisation

Similarly, after obtaining the optimised 3D models with their textures, they were exported to a 3D model viewer and a graphics engine: (1) Sketchfab, a 3D model viewer found on the web, available from any device with an internet connection, and (2) UE5, a video game graphics engine.

Sketchfab was selected as the primary 3D visualisation platform because of its web-based architecture, which enables cross-platform accessibility without the need for specialised software. This cloud-based approach significantly enhances the democratisation of 3D content by allowing universal access through standard web browsers on any internet-connected device, regardless of hardware specifications. This web-based testing environment served as an effective benchmark to validate whether our polygon reduction and texture projection techniques achieved optimal optimisation levels.

In parallel, the optimised models were imported into UE5 for critical evaluation under distinct parameter settings compared to those in Sketchfab. As a real-time rendering platform designed for interactive experiences, UE5 enabled comprehensive assessment of model performance under advanced lighting systems and their interoperability with native engine components. This phase specifically quantified the frame rate stability and rendering efficiency compared with their photogrammetric counterparts.

Testing the optimised 3D models in UE5 also allowed us to analyse their viability for applications beyond static representations. This includes their incorporation into video games, virtual reality, and augmented reality experiences.

8. Results and discussion

Therefore, 3D scanning using close-range photogrammetry allows detailed, high-fidelity 3D models of museum art pieces to be obtained, offering opportunities such as automatic orientation, measurement, 3D vector data, digital orthoimages, and digital surface models (Yastikli, 2007).

Thus, 3D models enable best practices aimed at the documentation of cultural heritage; moreover, they require fast and accurate software that efficiently contributes to digitisation while preserving texture, volume and details during the optimisation of 3D pieces (Gervasi et al., 2022).

(a) (b) (c)

Figure 3: Photogrammetric 3D models from Metashape: a) Santiago Crowned; b) Christ in Majesty; and c) David.

(a) (b) (c)

Figure 4: Meshes obtained after the retopology process: a) Santiago Crowned, Instant Meshes; b) Christ in Majesty, ZBrush; and c) David, Blender.

The digitisation process employed 210 photographs for Santiago Crowned, 310 for Christ in Majesty, and 360 for David. Images were captured at a distance of 50 cm from the object, resulting in a sampling distance of 0.0375 mm/pixel, which corresponds to the smallest identifiable element in the resulting 3D models.

As a result of the processing in Metashape, three 3D models were obtained, where the relief of the texture, the sharpness of the colours and the same distribution of volumes can be appreciated (Figure 3).

After a retopology process, new 3D geometry models were obtained; these meshes were lighter than those obtained by photogrammetry, with a LP density than the HP models (Figure 4).

The photogrammetric processing generated HP models with the following initial characteristics: Santiago Crowned (2.3 million polygons, 450 MB), Christ in Majesty (1.5 million polygons, 620 MB), and David (4.5 million polygons, 768 MB) (see Table S1). Table S1 also shows the final size after the optimisation process: 5 MB, 791 KB, and 1 MB, respectively. The final polygon counts of the optimised 3D models were 72000 (Santiago Crowned), 13000 (Christ in Majesty), and 10000 (David).

To quantitatively assess the geometric fidelity of the optimised models, a comparison between the original photogrammetric models and their optimised counterparts was performed using CloudCompare. Table S2 presents the results of the geometric analysis.

The results demonstrate that all optimised models preserve the original geometry with high fidelity. The bounding box dimensions are maintained above 99.5% in all the cases, whereas the surface area retention ranges from 90.3% to 99.2%.

The mean distance between the original and optimised surfaces is negligible (below 1.9 mm for Santiago Crowned, 5.7 mm for Christ in Majesty, and 10.6 mm for David), confirming that the retopology process does not introduce significant geometric distortion. The greater area loss observed in David (9.68%) corresponds to its greater complexity (4.5 M original polygons) and the manual retopology performed in Blender, which prioritised polygon reduction for real-time performance. The colour-coded heatmaps generated from the CloudCompare analysis are provided in the supplementary material (Figures S1-S3).

It should be noted that the RMSE values reported in Table S2 represent a statistical measure of geometric dispersion. The C2M distance calculation compares the sampled points of the optimised model against the surface of the original model, and the substantial difference in vertex density between the HP and LP models can influence the computed distances. However, the visual comparisons presented in Figures 8-10 confirm that these numerical values do not translate into perceptible geometric differences.

Therefore, the use of Instant Meshes, ZBrush and Blender resulted in 3D models with a significant reduction in polygon density. However, the new 3D models lack texture. The generation of UV maps allowed the transfer of information from the photogrammetrically generated part to the 3D models obtained by retopology through a texture projection process, thus maintaining the original appearance of the photogrammetric model on the optimised 3D piece (Knodt et al., 2023).

The texture projection generated four principal maps: (1) a colour map, for surface colour; (2) a normal map, for surface detail and light interaction; (3) an ambient occlusion map for self-shadowing; and (4) a roughness map for light scattering and surface reflectance.

Figure 5 shows the photogrammetric model (a) of Santiago Crowned, from which different information maps were extracted: (c) a colour map, (d) an ambient occlusion map, (e) a normal map and (f) a roughness map; and (h) the optimised model of Santiago Crowned with the information obtained from the photogrammetric model.

Similarly, Figure 6 shows the photogrammetric model (a) of Christ in Majesty, from which different information maps were extracted: (c) a colour map, (d) an ambient occlusion map, (e) a normal map and (f) a roughness map; and (h) the optimised model of Christ in Majesty with the information obtained from the photogrammetric model.

In addition Figure 7 shows the photogrammetric model (a) of David, from which different information maps were extracted: (c) a colour map, (d) an ambient occlusion map, (e) a normal map and (f) a roughness map; and (h) the optimised model of David with the information obtained from the photogrammetric model.

A comparative assessment of the three retopology software tools is presented in Table S3, including criteria such as cost, learning curve, user control, texture baking capability, and typical use cases. This comparison allows cultural heritage practitioners to select the most appropriate tool based on their specific project requirements (e.g., speed, precision, or minimum file size).

Therefore, the optimisation of 3D models obtained by photogrammetry using Instant Meshes, ZBrush and Blender software is appropriate, since it reduces the file size in MB of each piece while maintaining its original shape. The differences between each of them should be considered, such as their accessibility to the public.

Subsequent to the optimisation of the pieces, rendering tests were performed with different video graphics cards. The rendering time did not vary greatly across the different texture qualities: (1) 4k (4096x4096) pixels; (2) 2K (2048x2048) pixels; (3) 1K (1024x1024) pixels and 512x512 pixels. The video RAM (VRAM) requirement in all the cases was higher for the photogrammetric 3D models than for the optimised 3D models, in some cases up to four times higher (see Tables S3, S4 and S5).

Table S4 presents the results for the GTX 1060 graphics card. For Christ in Majesty, the optimised model achieved an average render time of approximately 22 s with a VRAM requirement of approximately 230 MB for a 4K texture, whereas the photogrammetric model took 22 s with 1104 MB of VRAM. For David, the optimised model showed an average of approximately 14 s with a requirement of 293 MB for a 4K texture, whereas the photogrammetric model needed 17 s and 608 MB of VRAM. For Santiago Crowned, the optimised model took approximately 14 s with 323 MB for 4K texture, whereas the photogrammetric model needed 16 s and 617 MB of VRAM.

Figure 5: Results obtained from the texture projection process on the 3D models of Santiago Crowned: a) photogrammetric model; b) photogrammetric mesh; c) colour map; d) ambient occlusion map; e) normal Map; f) roughness map; g) optimised 3D model; and h) all obtained maps combined into a material with the optimised 3D model of Santiago Crowned.

Figure 6: Results obtained from the texture projection process on the 3D models of Christ in Majesty: a) photogrammetric model; b) photogrammetric mesh; c) colour map; d) ambient occlusion map; e) normal map; f) roughness map; g) optimised 3D model; and h) all obtained maps combined into a material with the optimised 3D model of Christ in Majesty.

Figure 7: Results obtained from the texture projection process on the 3D models of David: a) photogrammetric model; b) photogrammetric mesh; c) colour map; d) ambient occlusion map; e) normal map; f) roughness map; g) optimised 3D model; and h) all obtained maps combined into a material with the optimised 3D model of David.

Table S5 presents the results for the RTX 2070 Super graphics card. Across all three artworks, the optimised models consistently required less VRAM (40–50% reduction) and shorter rendering times (30–40% reduction) compared to their photogrammetric counterparts. This improvement is largely attributed to the drastic reduction in polygon count achieved through retopology, which alleviates the memory bandwidth bottleneck, even when high-resolution 4K textures are used.

Table S6 presents the results for the RTX 3070 Ti graphics card. Although the more powerful GPU reduced absolute rendering times for both optimised and original models, the optimised models still demonstrated a clear advantage in VRAM efficiency, consuming up to 57% less memory (e.g., 639 MB vs. 1500 MB for Christ in Majesty). This reduction is particularly significant for real-time applications and multi-asset scenes, where VRAM is often the limiting factor. The fact that rendering times were nearly identical or slightly faster for the optimised models further confirms that geometric simplification does not compromise performance, even on high-end hardware.

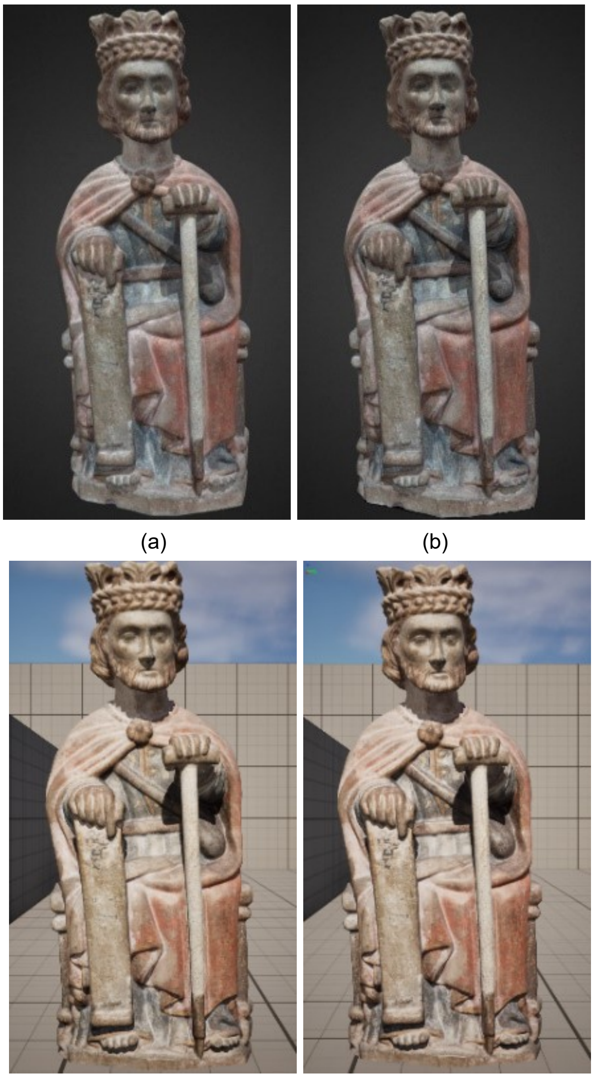
After being optimised the parts were integrated into two different applications with the same purpose: (1) Sketchfab, which is a visualizer for multipurpose 3D models on the web; and (2) UE5, a graphics engine designed for the creation of video games with a real-time rendering engine that, according to Autodesk (2024), allows the generation of real-time graphics that give the user interaction with the virtual environment, as used in video games to quickly represent movement.

Figures 8, 9 and 10 present visual comparisons between the photogrammetric models and the optimised models across two different platforms, a web viewer (Sketchfab) and a video game engine (UE5), showing no perceptible visual degradation at typical viewing distances. Although Sketchfab and UE5 are platforms with different purposes, the photogrammetric and optimised 3D models look similar (see Figures 8, 9 and 10); thus, it can be said that at first glance they are the same 3D model.

Figure 8 displays the 3D viewers in Sketchfab and UE5, where (a) represents the photogrammetric 3D model and (b) the optimised 3D model within Sketchfab. Moreover, in UE5, the photogrammetric model (c) shows no significant changes compared to the optimised model (d).

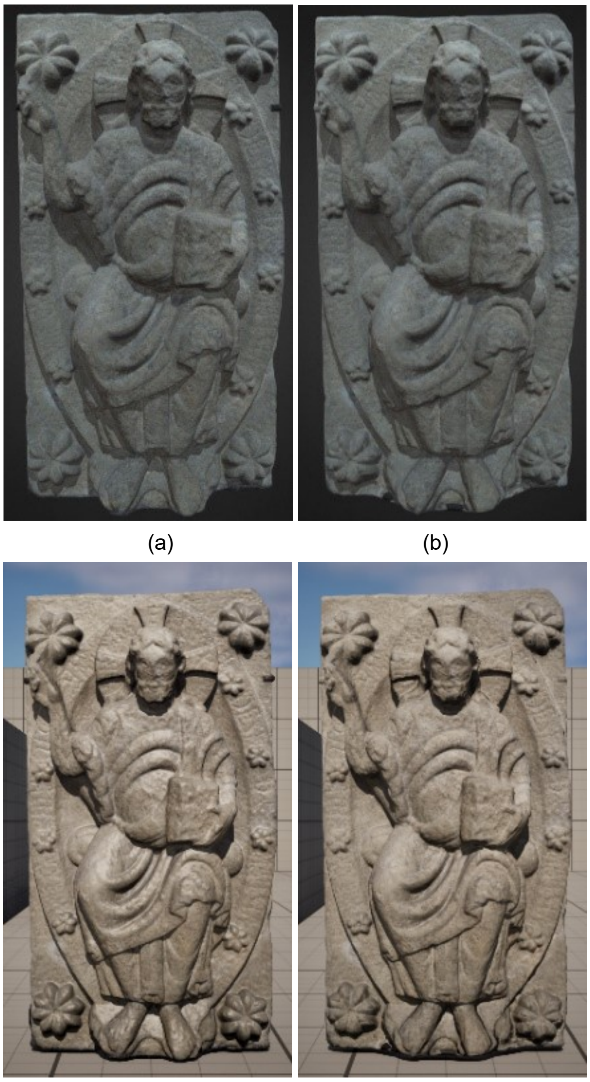
Figure 9 presents a comparative visualisation of 3D models using both platforms. The image shows the web viewer in Sketchfab displaying both the photogrammetric reconstruction (a) and optimised model (b). The image also displays a visual comparison in UE5, where (c) corresponds to the photogrammetric model and (d) represents the optimised model.

Figure 10 similarly presents a visual comparison between optimised and photogrammetric models within both Sketchfab and UE5. As observed, no significant geometric or colour discrepancies are evident between the photogrammetric and optimised 3D models. Visual comparison reveals consistent topological preservation across both model versions, suggesting effective optimisation while maintaining appearance.



(a) (b) (c) (d)

Figure 8: Visual comparison of Santiago Crowned original (photogrammetric) and optimised models across the two platforms: (a, b) Sketchfab web viewer; (c, d) Unreal Engine 5 real time engine. No perceptible visual differences are observed between the photogrammetric (a, c) and optimised (b, d) models at typical viewing distances.



(a) (b) (c) (d)

Figure 9: Visual comparison of Christ in Majesty original and optimised models across the two platforms. SketchFab web viewer (a, b); UE5 (c, d) real-time engine. The optimised models (b, d) preserve the visual appearance of the original (a, c) with no significant degradation.

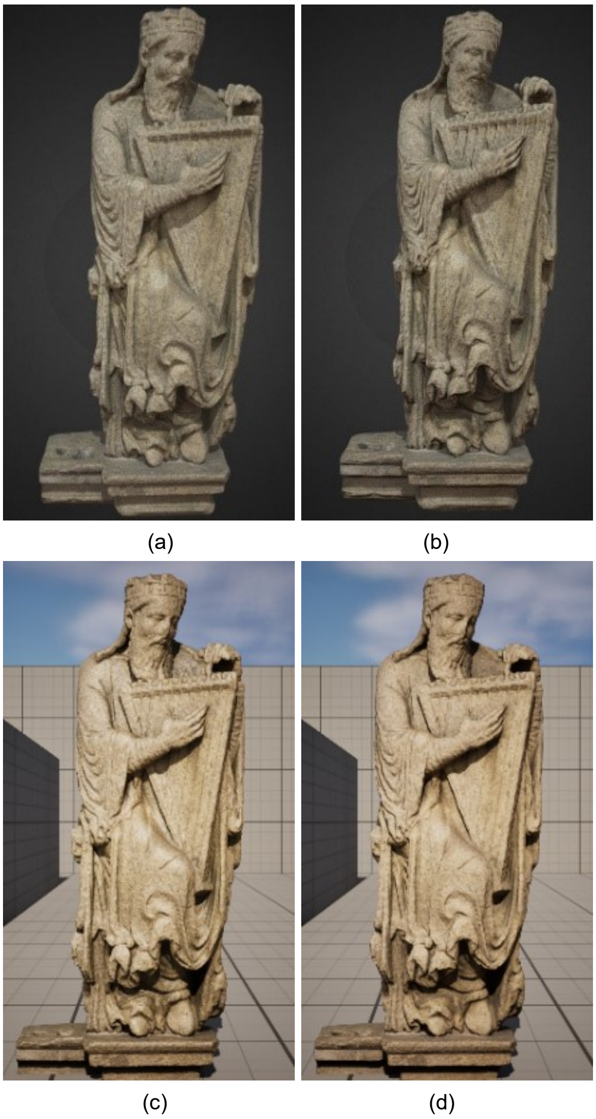


Figure 10: Visual comparison of David (photogrammetric) and optimised models. Sketchfab web viewer (a, b); UE5 (c, d) real-time engine. The optimised models (b, d) show no significant differences.

After the integration of the optimised and photogrammetric 3D models into UE5, the frame rate per second (FPS) and the rendering milliseconds (MS) of these models were measured, as shown in Table S6.

Table S7 shows the real-time performance of the optimised models on the entry-level GTX 1060. The improvements were most striking for the most complex original model, David, where the optimised version achieved approximately 120 FPS compared to only 50 FPS for the photogrammetric original—a 140% increase. Similarly, Christ in Majesty improved from 64 FPS to 119 FPS. Notably, rendering time (MS) variability was also substantially reduced: the photogrammetric models showed wide fluctuations (e.g., 8.4–12.6 ms for Santiago Crowned), whereas the optimised models remained stable within narrow ranges (e.g., 8.5–9.6 ms). These results indicate that retopology is particularly beneficial for lower-end GPUs, where polygon count and memory bandwidth are often the primary bottlenecks for real-time performance.

With respect to the RTX 2070, the performance gap between optimised and photogrammetric models narrowed compared to the GTX 1060, but the optimised versions still maintained a consistent advantage. For David, the optimised model achieved 87–92 FPS versus 80–83 FPS for the original. Although the absolute gains were smaller (approximately 10–15%), the optimised models again demonstrated lower rendering time variability (e.g., 11.23–12.30 ms for Santiago Crowned compared to 10.40–13.12 ms for the original). This suggests that as GPU power increases, the relative benefit of optimisation diminishes, yet it still contributes to smoother and more predictable performance—a critical factor for maintaining immersion in virtual reality environments.

With respect to the RTX 3070 Ti, the performance differences between optimised and photogrammetric models were minimal. Both versions ran at high frame rates (97–120 FPS), with the optimised models showing only a slight edge in maximum FPS and rendering time stability (e.g., 7.5–9.2 ms for optimised Santiago Crowned versus 8.9–9.2 ms for the original). This indicates that high-end hardware can largely compensate for geometric inefficiencies, making optimisation less critical for raw performance on powerful GPUs. However, as shown in Table S5, the optimised models still consumed significantly less VRAM (up to 57% less), which remains an advantage in multi-asset scenes or when running multiple applications concurrently. Therefore, even for high-end systems, optimisation is recommended to free up memory resources and improve overall system efficiency.

9. Conclusions

This study set out to determine an effective methodology for optimising HP photogrammetric models of cultural heritage artworks to enable their dissemination across resource-constrained platforms. The results demonstrate that retopology is a highly effective technique, achieving drastic reductions in file size (from hundreds of MB to a few MB) and polygon count while preserving visual fidelity, as validated in viewers such as Sketchfab and real-time engines such as Unreal Engine 5.

Quantitative geometric assessment using CloudCompare confirmed that all optimised models preserved the original geometry with high fidelity: the bounding box dimensions were maintained above 99.5%, the surface area retention ranged from 90.3% to 99.2%, and the maximum surface deviation remained below 1.9 mm (Santiago Crowned), 5.7 mm (Christ in Majesty), and 10.6 mm (David). These results support the visual observations and demonstrate that the retopology process does not introduce significant geometric distortion.

This optimisation is not merely a technical step but also a crucial strategy for digital preservation and democratising access to heritage, allowing high-quality 3D assets to run on common hardware and mobile devices.

The comparative analysis of three retopology tools yielded a clear hierarchy of effectiveness for this specific use case. Instant Meshes emerged as the most efficient solution, offering an optimal balance between automation, speed, and geometric preservation. It is the recommended tool for projects prioritising rapid processing with minimal manual intervention.

Blender proved to be the most precise and flexible tool, essential for manually correcting complex areas (e.g., sculptural details) where automated methods may fail, despite requiring more time and expertise. ZBrush, while functional, offered intermediate results, being less consistent than Instant Meshes in preserving structure for subsequent texturing.

The practical validation confirmed the core hypothesis: optimised models significantly improve performance in real-time environments. In Unreal Engine 5, they consistently showed higher FPS and lower rendering times than their photogrammetric counterparts did, whereas they reduced GPU memory (VRAM) usage by up to 75% in some tests. Crucially, this performance gain was achieved without perceptible visual degradation at standard viewing distances, ensuring that the authenticity of the digital artefact is maintained.

Therefore, in answer to the research question, optimising 3D photogrammetric models in museums is critically recommended to bridge the gap between archival-quality digitisation and public accessibility. The choice of tool can follow a two-stage workflow for optimal results: using Instant Meshes for fast, bulk optimisation, followed by selective refinement in Blender for critical pieces requiring the highest precision. This approach provides cultural institutions with a viable, cost-effective pipeline to create lightweight, high-fidelity digital surrogates that can fuel virtual exhibitions, educational applications, and immersive experiences, thereby safeguarding and sharing our collective heritage in the digital age.

Acknowledgements

Special thanks are extended to the Santiago de Compostela Cathedral Foundation, and to the director of the Santiago Cathedral Museum, Mr. Ramón Yzquierdo Peiró. The authors would like to thank the Editor-in-Chief for careful attention, constructive guidance and valuable support throughout the editorial process.

Supplementary files

This article contains supplementary files accessible via https://doi.org/10.4995/var.2024.25621

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