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EMPLEO DE INTELIGENCIA ARTIFICIAL PARA SÍNTESIS DE MATERIALES BASADOS EN FÍSICA EN RECONSTRUCCIÓN PATRIMONIAL

AI-DRIVEN SYNTHESIS OF PBR MATERIALS FOR VIRTUAL HERITAGE RECONSTRUCTION

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RESUMEN: La digitalización del patrimonio arquitectónico evoluciona desde la documentación hacia un instrumento transversal de investigación, conservación preventiva y divulgación, donde la visualización 3D con renderización se basa en la demanda de materiales digitales plausibles para sostener la credibilidad de la representación. Sin embargo, la paradoja metodológica de las técnicas reality-based (fotogrametría y TLS) capturan con alta fidelidad geométrica el estado actual del bien, así como el registro de deterioros, pátinas y alteraciones que dificultan la materialidad histórica original como el caso de la erosión y las alteraciones cromáticas del granito fino ornamentado que oscurecen la apariencia primigenia de la Iglesia de Santa María de Sar en Santiago de Compostela. Por ello, este trabajo aborda la brecha entre lo existente-degradado y lo original-perdido mediante un método aplicado que desarrolla y documenta un flujo de trabajo integral para la síntesis de materiales PBR asistida por IA multimodal, integrado en un pipeline profesional (GIMP + Blender/Cycles). Los hallazgos técnicos muestran que la generación del albedo toma aproximadamente tres minutos, el resto de mapas PBR se derivan sistemáticamente en GIMP y se integran posteriormente en Blender. Desde la ética, se identifica que los modelos de IA crean debido a sus datos de entrenamiento, lo que exige una documentación explicita de paradatos, asi los resultados demuestran que, bajo dirección experta la IA produce materiales PBR plausibles, concluyendo que el método es técnicamente viable y estéticamente coherente para divulgación e hipótesis de restitución, sin sustituir a la captura directa ni exime de la transparencia metodológica.

Palabras clave: patrimonio cultural, patrimonio cultural digital, modelado 3D, materiales PBR, ingeniería de instrucciones

ABSTRACT: The digitization of architectural heritage is evolving from mere documentation into a cross-cutting tool for research, preventive conservation, and dissemination, where 3D visualization with rendering relies on the demand for plausible digital materials to support the credibility of the representation. However, a

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methodological paradox arises with reality-based techniques (photogrammetry and TLS), which capture the current state of the asset with high geometric fidelity, including the recording of deterioration, patinas, and alterations that obscure the original historical materiality—as in the case of erosion and chromatic alterations of fine ornamental granite that mask the original appearance of the Church of Santa María de Sar in Santiago de Compostela. Therefore, this work addresses the gap between the existing-degraded and the original-lost through an applied method that develops and documents a comprehensive workflow for the synthesis of PBR materials assisted by multimodal AI, integrated into a professional pipeline (GIMP + Blender/Cycles). The technical findings show that albedo generation takes approximately three minutes, the remaining PBR maps are systematically derived in GIMP and subsequently integrated into Blender. From an ethical perspective, AI models are found to introduce biases due to their training data, requiring explicit paradata documentation. Thus, the results demonstrate that, under expert guidance, AI produces plausible PBR materials, concluding that the method is technically viable and aesthetically coherent for dissemination and restitution hypotheses, without replacing direct capture or exempting methodological transparency.

Keywords: cultural heritage, digital cultural heritage, 3D modeling, PBR materials, prompt engineering

INTRODUCTION

The digitization of architectural heritage expands the virtual scope from registration to a transversal instrument for research, preventive conservation and public access. In this context, physics-based rendering (PBR) flows become widespread in heritage 3D visualization associated with the search for materially credible representations; The credibility of the visualization depends critically on the quality and plausibility of the digital materials applied to the model (1, 2, 3, 4).

However, there is a fundamental methodological paradox: while techniques such as photogrammetry and terrestrial laser scanning (TLS) allow the generation of reality-based 3D models with high geometric fidelity to document the current state of heritage assets, said state usually incorporates deterioration and interventions that make the inference of the original historical materiality difficult (5, 6, 7, 8, 9, 10). This discordance is manifested with particular acuity in the Church of Santa María de Sar, where ornamental elements in fine granite present surface erosion and chromatic alterations that obscure their original appearance.

Contemporary theory of digital heritage recognizes that all digital representation is inherently interpretive, placing itself between the documentation of the existing state and the hypothesis of disappeared states (11, 12, 13). This spectrum requires methodological transparency through paradata, a fundamental ethical requirement according to the London Charter (2009) (14) and the Seville Principles (2017) (15) because it implies a double challenge: technical and interpretive.

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Conventional methods of creating digital heritage materials have two categories: (1) photogrammetry which is the standard for documenting existing heritage by producing textures that record pathologies and degradation (16, 17, 18) although, Vico-García et al. (2025) (19) point out that cleaning these textures of anachronistic elements is complex and destructive. Therefore, in cases of substantial material loss, photogrammetry would lack reliable data (11). Consequently, (2) manual modeling is the alternative of creating hypothetical materials with the synthesis of historical information and architectural analogues (20). Although this approach is time intensive, its quality will depend on the subjective skill of the creator because its process would rarely be reproducible or transparent, since it would have the risk of reflecting contemporary aesthetic conceptions (11, 21).

Contextually, generative Artificial Intelligence (AI) models, in particular multimodal systems conferring natural language processing and image synthesis, propose new possibilities for cultural heritage (22). Models that operate as statistical inference systems because they learn probability distributions over millions of text-image pairs to originate new images corresponding to textual descriptions (23). Therefore, the initial applications of AI in cultural heritage focus on virtual restoration of images, categorization of artifacts or production of stylistic variants (11, 22). However, the specific application to PBR texture synthesis for virtual architectural reconstruction represents a theoretically unexplored domain with obstacles such as the scarcity of paired data sets and multichannel coherence problems (24, 25, 26).

This application must take into account fundamental precautions, as generative AI models turn out to be biased by their training data extracted from the contemporary internet, suggesting the risk of generating anachronistic views of heritage (27). Furthermore, their stochastic nature clashes with the ideal of scientific reproducibility (28), and critical digital heritage theory emphasizes that these technologies reconfigure relations of interpretive authority (29).

In response, the research proposes a dual objective: to develop and document a comprehensive workflow that employs multimodal AI models (GPT-4 with DALL-E 3) to create PBR materials intended for virtual heritage reconstruction; and apply this protocol to the synthesis of textures of the original fine granite of the Church of Santa María de Sar. The research is articulated around the question of what level of aesthetic coherence and technical feasibility is necessary for the process to be considered methodologically valid when deployed within a rigorous protocol that starts from a contextually anchored historical specification, follows an iterative prompt engineering process and culminates in specialized post-processing.

The validity evaluation operates in two interdependent dimensions: contextual aesthetic coherence, defined as the degree to which a generated texture is perceived as plausible and integrable in a 3D model according to expert evaluation based on historical-material knowledge; and reproducible technical feasibility, referring to the ability of an AI output to be processed and integrated into a standard PBR production workflow to generate a physically coherent renderable material (30). These criteria are intertwined with the concept of heritage prompt engineering, understood as the systematic process of translating historical-material knowledge into precise instructions

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to direct a generative model, an emerging practice as a specialized competence at the intersection between historical research, materials science and computational linguistics.

The fundamentality of this research lies in its methodological contribution, closing the gap between the emerging capabilities of AI and the needs of heritage visibility through a structured and reproducible workflow to technically demonstrate the integration of AI outputs in professional pipelines (Blender/Cycles) and theoretically advance the discussion of the validity criteria for the evaluation of digital reconstructions that use generative technologies and, open a debate of the intersection of digital heritage and computational ethics (31, 32).

MATERIALS AND METHODS

This research takes an applied method approach, given that the central objective is to design, document and evaluate a specific technical procedure for the resolution of a practical problem, such as the efficient generation of hypothetical PBR materials for digital heritage.

While a methodology constitutes the framework that justifies the why of the research, a method describes the operational how (33). In this case, the what is the evaluation of the viability of AI for synthesis of heritage textures; the why is exposed in the theoretical framework, based on an interpretive-critical paradigm; and the how is the five-phase workflow. It is a method for developing and evaluating prototypes in digital humanities that follows a linear and descriptive logic, common in technological feasibility studies applied to heritage, where rigor lies in the descriptive transparency and reproducibility of the process (34).

The nature of the problem is not amenable to standardized quantitative measurement, as there are no universally accepted metrics to measure the historical coherence of a texture. Validation is based on an expert qualitative evaluation, taking into account criteria of aesthetic-historical coherence and technical functionality, through direct observation and critical analysis of the visual results, an approach consistent with design-based research (35). The validity of the method is derived from the observed feasibility of the process and the credibility of the results before a specialized audience.

The implementation required three tools. ChatGPT Plus (GPT-5.2 with DALL-E 3) was used for image synthesis. Image processing was performed in GIMP 3.0.6. Materials integration and visual validation were carried out in Blender 4.5 with its Cycles engine to evaluate physical properties under controlled lighting (Table 1).

Table 1. Technical specifications of the programs and computer used.

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Component	***Specification***
Image synthesis	ChatGPT plus (DALL-E 3)
Texture processing	GIMP 3.0.6
3D modeling and texturing	Blender 4.5 / Cycles
Minimum recommended hardware	
Processor	Ryzen 7 3700X
Ram Memory	16 GB DDR4
Graphics card	NVIDIA RTX 2060 6GB
Storage	SSD 256 GB
Internet connection	Used by ChatGPT

The applied method is articulated in five consecutive phases, illustrated in Figure 1, which transform a historical specification into a digital material. Below, each phase is broken down with its intermediate outputs and the difficulties encountered.

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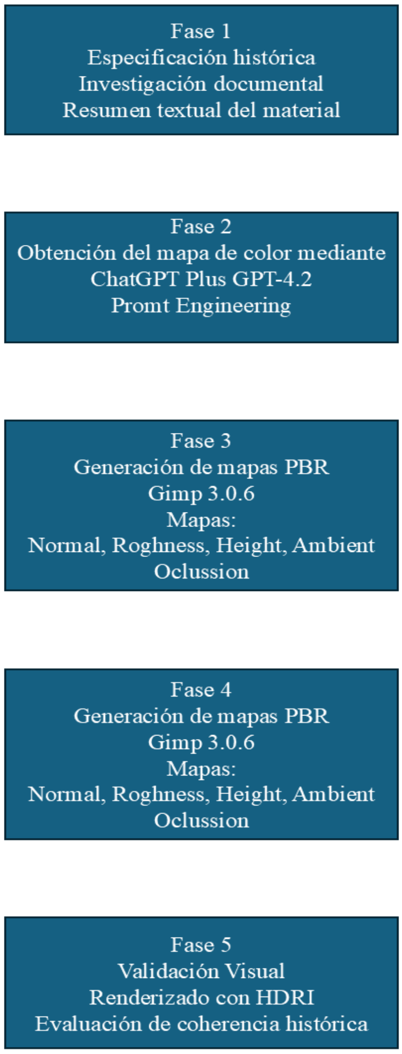

Figure 1. Diagram of the proposed workflow for the synthesis of PBR materials.

Source: own elaboration.

2.1 Phase 1: Historical specification and documentary research

This phase represents the first stage of the workflow used, which translates the historical research into a textual description, in this case it will define the characteristics of the original fine beige granite, excluding patinas and documented deterioration, in addition to selecting the images that will serve as a reference for the material.

2.2 Phase 2: Base texture synthesis using AI

The next phase is the adaptation of the generated textual description to obtain an approximate result, since the reference images include damage from patina, moss and shadows, it is necessary to overcome them with the adjustment due to the promt. The textual description used to solve this was: "Based on the images provided, create a seamless, 2k, albedo map of fine granite sandstone for the base of a PBR material."

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2.3 Phase 3. Generation of PBR maps in GIMP

The result obtained after the synthesis process using ChatGPT will be intervened using GIMP, focused on deriving the complementary maps. For the normals map, the albedo was converted to grayscale and the Normals Map filter was applied, adjusting the depth to obtain subtle micro-surface relief.

The roughness map was obtained by manipulating the same grayscale image; The tones were inverted and the contrast was adjusted to assign low roughness values to light areas and high values to dark areas. The height map was derived from the gray version of the albedo, applying Gaussian Blur and enhancing the contrast. The ambient occlusion map was generated from the height map; Gaussian Blur was applied and Levels were adjusted to selectively darken cracks and seams. Each map was adjusted to maintain physical and visual consistency with the albedo.

2.4 Phase 4: Integration into Blender

The 5 maps generated, both by AI and by GIMP, are integrated into Blender following the standard flow established for PBR materials. Thus, these maps make up a digital material that is applied to the corresponding 3D model, configuring the UV coordinates and texture scale to guarantee realistic use.

2.5 Phase 5: Visual validation

The last phase corresponds to visual validation using test renders with HDRI lighting, which allows evaluating the visual coherence of the material, its physical response to light and its integration into a rendered virtual environment.

It should be noted that this study adopts an applied method whose central purpose is to document and evaluate a specific technical procedure designed to solve a practical problem in heritage visualization. The method is based on the observed viability of the process and the qualitative evaluation of the result based on criteria of aesthetic-historical coherence and technical functionality in a PBR environment. Figure 1 schematizes the operational sequence of the five phases that make up this workflow, from the conceptual definition of the material to its final validation as a digital asset, where each phase represents a specific functional module within the production pipeline.

RESULTS

This section presents the visual results obtained in each phase of the workflow, demonstrating the feasibility of the proposed method to generate heritage PBR materials using AI.

The execution began in the ChatGPT interface, which introduced a specific textual description and a prompt that combined technical production requirements (2K resolution, seamless format, albedo map type) with a specific detail of historical material ("fine granite sandstone").

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To visually support this specification, two reference images were provided to the model: 1) a sample of pure granite that defined the target texture, and 2) a photograph of an existing medieval arch in Santa María de Sar, built with the same material, which provided architectural context and historical validation. This multimodal prompt engineering approach allowed the DALL-E 3 model to be directed towards the generation of a base image conceptually aligned with the heritage restitution objectives (Figures 2 and 3).

Figure 2a shows a detail of the medieval arch of Santa María de Sar, built with the sandstone granite that constitutes the case study, while 2b is a reference sample of the same material, which defines the target texture. Both images were provided to the AI as visual context to guide the generation of the albedo map technically specified in the textual prompt.

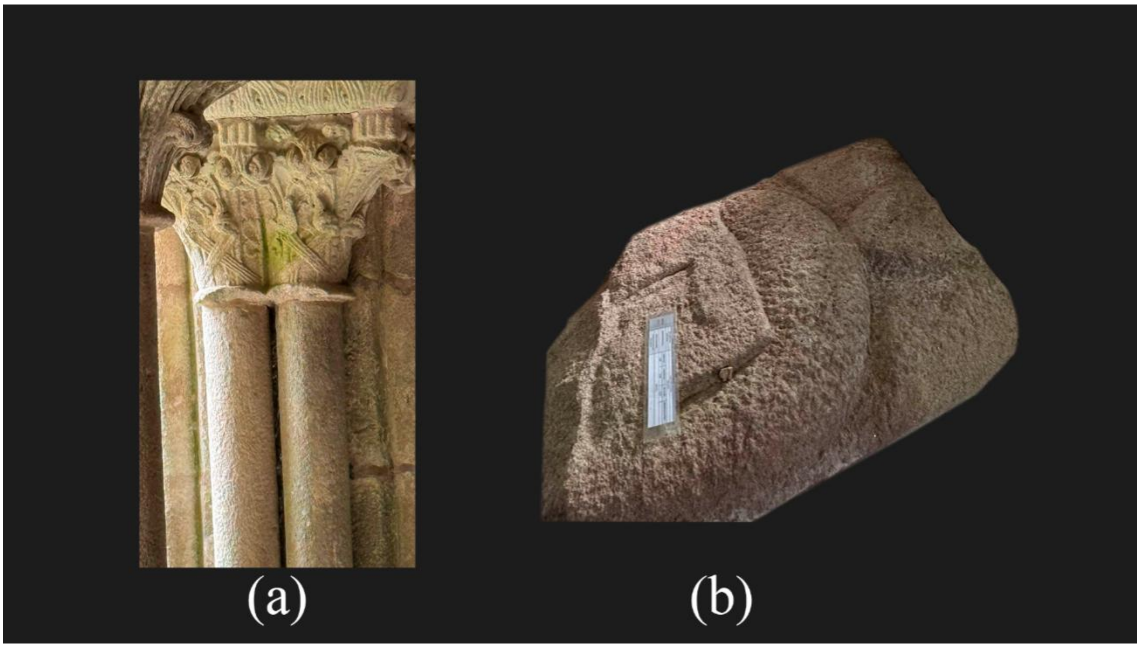

Figure 2. Reference images.

Source: own elaboration.

Figure 3 documents the result of the AI synthesis phase, and by capturing the ChatGPT interface it shows the exact prompt that specified the technical requirements and material context. The generated image, produced in approximately three minutes, corresponds to an albedo map with the requested characteristics, received in seamless format and with neutralized lighting, ready for subsequent processing.

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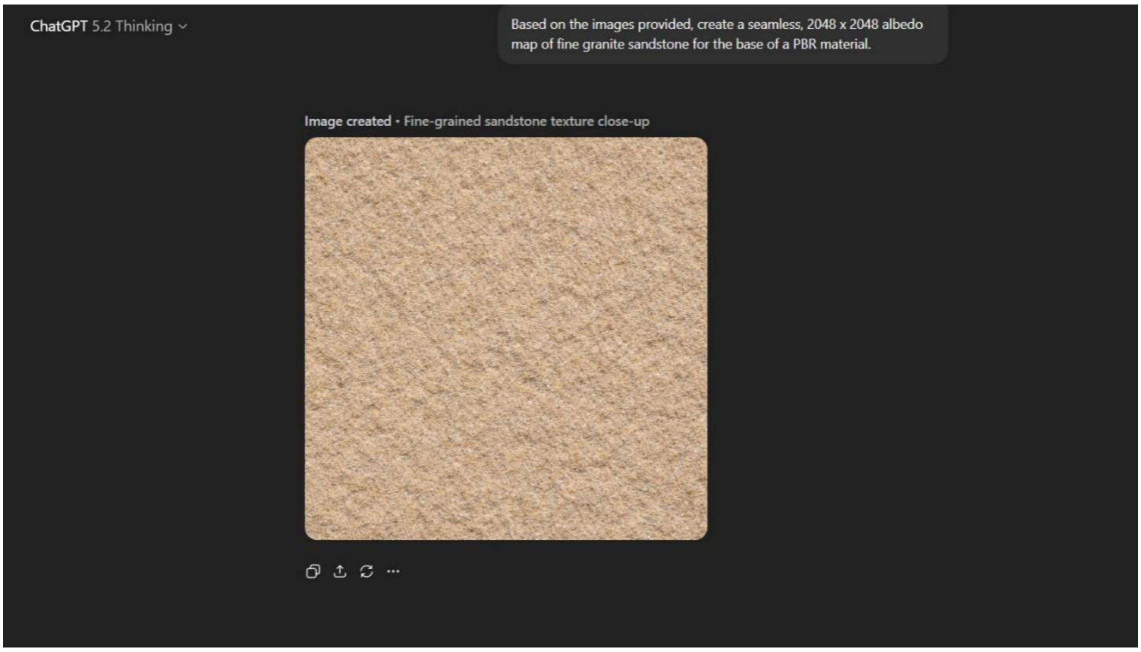

Figure 3. AI synthesis process in ChatGPT.

Source: own elaboration.

In this way, based on the albedo map synthesized by the AI, we proceeded to generate the complete set of maps that make up a physically coherent PBR material within the GIMP environment. This critical derivation step converted the base image into a material system ready for realistic rendering (Figure 4).

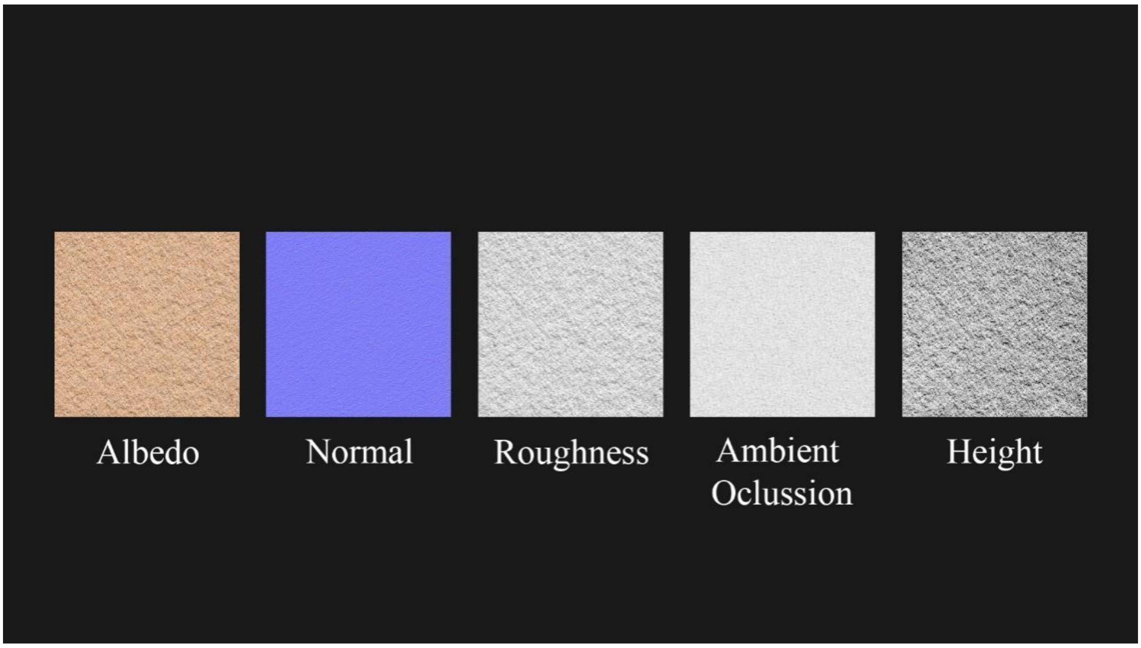

Figure 4. Resulting maps after post-processing in Gimp.

Source: own elaboration.

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Figure 4 shows the set of PBR maps derived by Gimp from the AI-synthesized Albedo. The figure shows the entire set of maps that together make up the physically based material: Albedo, which gives the color to the material; Normal, which is responsible for the surface micro-geometry of the granite; Roughness, which defines the variation of specular gloss; Ambient occlusion (AO), which simulates shading in concavities and joints; and Height map, intended for displacement or parallax effects. The visual consistency between the maps confirms the validity of the AI-generated albedo as a basis for a physically plausible derivation.

After obtaining all the maps that make up the PBR material, albedo, normals, roughness, height and ambient occlusion, the next phase consisted of its technical integration within the Blender environment. To do this, a material was configured under the Cycles rendering engine within the node editor, where it is evident how these five maps are systematically connected to the corresponding inputs of the Principal BSDF shader.

This nodal configuration is fundamental, since it establishes the precise physical relationships between the surface properties defined by each texture, transforming the set of independent images into a unified digital material, physically coherent and ready to be applied to the geometry of the heritage model (figure 5).

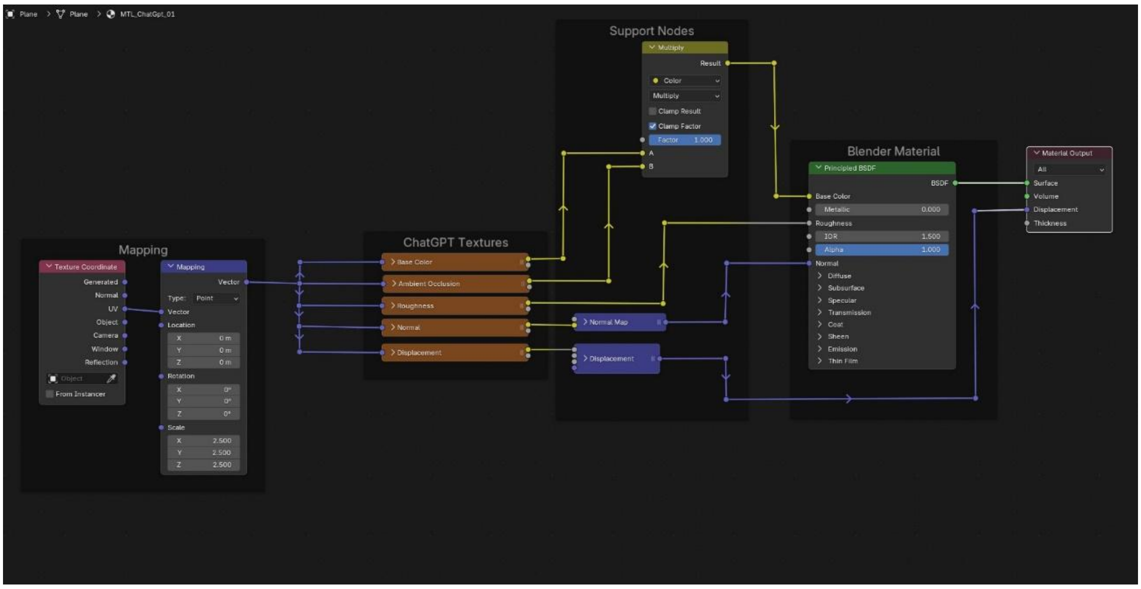

Figure 5. Material nodal configuration in Blender.

Source: own elaboration.

Screenshot of the node editor showing the systematic connection of the five generated texture maps (Figure 5) (albedo, normal, roughness, height and ambient occlusion) to their corresponding input sockets in a Principled BSDF shader. This configuration establishes the physical relationships between surface properties, transforming the independent images into a unified digital material ready for application in the heritage 3D model.

After the creation of the material and its correct configuration in the node editor, a preliminary validation phase was carried out by assigning it to primitive test geometries

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– a plane, a cube and a cylinder. This step allowed the physical behavior of the material to be verified in situ under different surface orientations and lighting conditions, ensuring the coherence of the PBR maps and the absence of visual artifacts before their final application to the historic ornamental element of the Church of Saint Mary of Sar (figure 6).

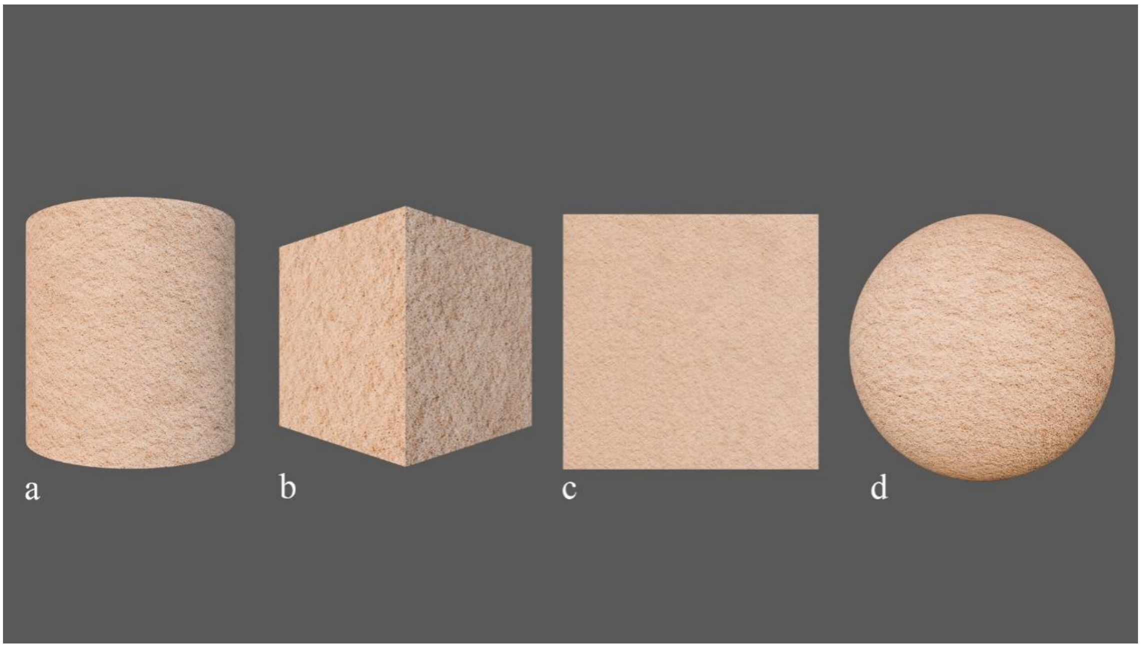

Figure 6. Preliminary validation in primitive geometries.

Source: own elaboration.

Figure 6 shows the render of the final PBR material applied to basic 3D models (cylinder, cube, plane, sphere) to evaluate its physical behavior under different surface orientations and controlled lighting conditions. This stage allowed us to verify the coherence of the maps, the correct projection of the textures and the unified visual response of the material before its assignment to the historical heritage element.

After preliminary verification in test geometries, the final visual validation was carried out by assigning the material to a specific heritage element: an ornate capital located in the interior ceiling of the central nave of the Church of Santa María de Sar. For this evaluation, HDRi ambient lighting was used, which simulates realistic lighting conditions and allows a comprehensive evaluation of the physical response of the material, its interaction with light, specular behavior and relief perception, as well as its visual coherence within the historical architectural context for which it was conceived (Figure 7).

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Figure 7. Final validation in heritage context.

Source: own elaboration

Figure 7 is a render of an ornate capital from the interior of the church of Santa María de Sar with the PBR material applied. The evaluation was carried out under HDRi lighting, which made it possible to analyze in situ the physical response of the material, its realistic interaction with light, specular behavior and the perception of relief and its visual coherence within the historical architectural context for which it was conceived.

The final integration of the synthesized material into the target heritage element, together with the complete set of PBR maps and their documented technical configuration, constitutes the tangible result of the proposed workflow. These visual and technical results, however, open a series of questions about the effectiveness, limitations and methodological significance of the process carried out, aspects that will be critically analyzed in the following discussion section.

DISCUSSION

The successful implementation of the workflow poses an affirmative, albeit nuanced, answer to the research question regarding the technical feasibility and aesthetic coherence of integrating generative AI into the production of heritage PBR materials. The technical feasibility is demonstrated not only in the temporal efficiency with the generation of the albedo in minutes radically contrasting with the hours or days of subjective manual modeling (24) or with the complex processing of photogrammetry to clean degraded textures, but in the perfect integration of the synthetic output in a standard industrial PBR pipeline.

However, this efficiency comes with a transfer of workload: while traditional methods such as photogrammetry, although accurate, inevitably capture current deterioration, requiring hours or days of manual texture cleaning to remove patinas and anachronistic alterations (16, 17, 19). For its part, manual modeling allows greater creative control,

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but its quality depends critically on the subjective skill of the digital artist, with production times that can extend to several days per material (20, 21). In contrast, the method proposed here shifts the critical effort from the technical execution to the historical specification and prompt engineering phase, reducing the generation of the albedo to minutes, although transferring the expertise to the domain of historical research and the management of the AI model (23, 27).

Thus, aesthetic coherence reaches a level of contextualized historical plausibility, that is, a criterion different from the documentary quality of traditional methods. Well, photogrammetry provides an accurate representation of the current state of deterioration; Therefore, manual modeling often promises a historically accurate recreation that is limited by the creator's subjective skill and interpretation.

Then, AI guided by site-specific visual references (Fig. 2) created a texture that contextually evoked the historical material to fill a gap between the existing and the hypothesis of the lost; although this capacity has been structurally limited by the stochastic nature and biases of diffusion models. Thus, unlike a laser scanner and/or a metric camera, DALL-E 3 which does not measure or usually replicate; was interpreted based on statistical distributions of the training set. This makes it prone to generating anomalies or generic textures ("average stone") when the references are ambiguous or the prompt is imprecise, a risk that does not exist in direct capture methods.

These technical limitations are intrinsically linked to profound ethical implications. The use of generative AI in cultural heritage reactivates classic debates about authenticity and interpretive authority (29). A model trained predominantly with internet data perpetuates and amplifies contemporary cultural and aesthetic biases, potentially generating an anachronistic or Westernized view of historical materials.

Therefore, transparency (paradata) is an ethical imperative that any application of this method must specifically declare the synthetic and/or interpretive nature of the textures by differentiating them from the direct capture data and/or documented during the prompt engineering process, as well as the references used. Which causes alignment with the principles of the London Charter (2009) (14) to avoid the creation of a speculative heritage with the false authority of a historical document.

The practical implications are dual because, on the one hand, this technology partially democratizes the origin of high-fidelity materials, since it allows teams with fewer resources specialized in digital art to create visual prototypes for feasibility studies with financing proposals and/or educational experiences. Thus, on the other hand, a new dependence on platforms and commercial models arises whose algorithms, costs and conditions of use tend to change arbitrarily with the vulnerability that it does not affect traditional methods based on open source software and/or autonomous photogrammetric techniques.

The future of this line of work should focus only on developing domain-specific models trained with ethically curated heritage corpora, and integrating AI hybridly; for example, by using photogrammetry to provide geometry and macrotextual structure, and by using AI to infer and synthesize micro-texture and missing original colors. In this way, AI would

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not replace methodologies, but would be integrated to overcome their respective limitations under a framework of transparency and critical rigor for the researcher and/or creator, and not the algorithm as an authority in the interpretation of the past.

CONCLUSIONS

This study developed and validated an operational workflow that integrated AI synthesis into the production of PBR materials for historical heritage visualization. The results demonstrated that, under a framework of precise historical specification and prompt engineering, it is possible to create digital materials with correct aesthetic-historical plausibility for dissemination contexts, preliminary studies and/or restitution hypotheses.

The main answer to the research question was affirmative because the integration of generative AI in this pipeline was technically feasible and, aesthetically, coherent, although its value did not lie in automation, but in the formalization of a new translation process.

Thus, the method became expert knowledge and a replicable history protocol that can direct the future and synthetic generation towards a specific heritage objective by surpassing mere random generation.

However, as evidence, this capacity remains, which does not replace material evidence or direct capture; On the contrary, it reconfigured the role of the researcher and/or creator from manual executor to AI director because his critical authority was exercised in the specification and validation phase, not in the execution phase.

Therefore, the ultimate contribution of this work transcended as the specific technical result by offering a methodologically transparent model that documented step by step its adaptability and improvement by the community. It is then that he raises and also asks a fundamental question for the future of digital humanity: how will AI tools be designed that not only accelerate processes, but also amplify and formalize the interpretive rigor of the specialist?

Therefore, it is recommended that future research explores (1) the development of standardized prompts for categories of historical heritage materials, (2) hybrid integration with photogrammetry data to guide the synthesis geometrically, and the (3) creation of domain-specific models trained with curated heritage corpora.

Because only in this way will AI stop representing a unitary creative black box and become a critical, analytical, reproducible and ethical instrument that will serve the interpretation and communication of digital historical heritage.

In short, this research is presented as a complementary tool to a digital kit for the historical heritage specialist because it validates contexts where the balance between efficiency, historical plausibility and methodological transparency of the space is explicit and ethically managed.

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