heritage

MDPI

Article

An Integrated Method for the Reconstruction of Private Renaissance Exhibition Rooms (*camerini*) Starting from Ippolito II d'Este's Cabinet of Paintings at His Tiburtine Villa

Carmelo Occhipinti [1], Olga Concetta Patroni [1], Marco Gaiani [2,*], Luca Cipriani [2] and Filippo Fantini [2,*]

[1] Department of Literature, Philosophy and Art History (ALEF), University of Rome Tor Vergata, 00133 Rome, Italy; cchcml00@uniroma2.it (C.O.); olga.concetta.patroni@uniroma2.it (O.C.P.)

[2] Department of Architecture, Alma Mater Studiorum University of Bologna, 40136 Bologna, Italy; luca.cipriani@unibo.it (L.C.)

* Correspondence: marco.gaiani@unibo.it (M.G.); filippo.fantini2@unibo.it (F.F.)

Abstract: This paper presents a new object of study—the so-called *camerini*, private rooms for study and reflection in the great stately palaces of the fifteenth and sixteenth centuries, which contained riches and artistic heritage of inestimable value and were characterized by very dim lighting. Analysis of the *camerini*, true precursors of the modern museum, is not only study of a specific subject but also extremely relevant because it allows us to reanalyze the entire evolution of the museum type and its characteristics, discovering its origins, following its evolution, and critically reviewing its current features. Starting from the case study of the *Quarto Camerino* of the Villa d'Este in Tivoli, a superset of the specific features of this type of space and possible problems in its 3D reconstruction, this article presents a method and a workflow aimed at reconstruction and visualization, with high visual quality of these spaces and their features. Digital surveying technologies were integrated with advanced methods that allowed for the reproduction of the full optical properties of spatial surfaces and with tools for semantic modeling and visualization to generate a digital artifact that is consistent with the available information and its interpretations and that can be analyzed both perceptually and analytically.

Keywords: cultural heritage; history of art and architecture; virtual reality; virtual reconstruction; camerino; physically based shading

Academic Editor: Andreas Aristidou

Received: 17 December 2024
Revised: 23 January 2025
Accepted: 23 January 2025
Published: 28 January 2025

Citation: Occhipinti, C.; Patroni, O.C.; Gaiani, M.; Cipriani, L.; Fantini, F. An Integrated Method for the Reconstruction of Private Exhibition Rooms (*camerini*) from the Renaissance, the case study of Ippolito II d'Este's Cabinet of Paintings at His Tiburtine Villa. *Heritage* **2025**, *8*, 54. https://doi.org/10.3390/heritage8020054

1. Introduction

Art historians and collection historians have not focused on the capital importance of the Greek word *museion* until now. Originally referring, according to Strabo's well-known statement, to cult places consecrated to the Muses, forgotten throughout the Middle Ages, it was first exhumed by Erasmus of Rotterdam in two of his different texts, the *Colloquia* and the *Convivium religiosum* (1522–1523), in reference to his own very private place of study, within which the Dutch humanist said he had placed his entire world (*mundum meum*) [1]. This place of study, which he defined in Greek as *museion* and connected, not surprisingly, to the library (*adiunctus est bibliothecae*), had the characteristics of being small (*angustus*), elegant (*elegans*), and, above all, dark (*obscurus*). In fact, the darkness and semi-darkness were meant to promote the humanist's recollection and concentration, also enabling them to imagine the immense and lost magnificence of ancient Greece and the Rome of the Caesars not only through the reading of literary texts but also through the vision of those precious artifacts that, lovingly guarded, precisely, in the shade of the *museum*, were revealed in the light of a dim and flickering flame to make *elegant* that *cramped* and *dark* place. Just a little later, in 1532, the word *museion* was attested to in the correspondence of Benedetto, Paolo Giovio's brother, in reference to the palace, then under construction on Lake Como, where what everyone would later come to know as the Giovian *museum* was being built, inspired by the Plinian villa and adorned inside with the enormous collection of portraits of illustrious men of whom the Como historian was weaving the Elogia [2]. Beginning from 1552, those portraits were replicated at the request of Cosimo I de' Medici to embellish the Sala del Mappamondo in the Palazzo Vecchio and later, as we still see today, the Uffizi Gallery; thus, the term *museum* made its appearance in the text of the first edition of Giorgio Vasari's *Lives* (1550), where one would encounter it exclusively referring, still, to the Jovian enterprise [3]. Shortly thereafter, however, the meaning of the term *museum* would end up changing to that of gallery.

By the middle of the 15th century, the humanistic practice of the study space decorated with antiquities—to which Erasmus meant to refer—had taken root in many Italian courts. *Cubiculum* was one of the terms that started to be used at that time to describe that specific setting that was dedicated to the study and appreciation of little antiquities. According to Pliny the Elder (Nat. hist. 35, 4) and Vitruvius, who also alluded to a potential relationship between *cubiculum* and *bibliotheca* (De arch. VI, 4), *cubiculum* in classical Latin denoted a rest room that was provided with a bed and occasionally decorated with images. Regretfully, we lack accurate knowledge regarding the furnishings and decorations of the imperial era's *cubicula*. What is known, though, is that these secluded chambers were small enough to encourage recollection, and it is easy to imagine that they were dimly lit because they were places of rest.

Following the iconological program elaborated by Guarino da Verona in Ferrara between 1447 and 1463, Lionello d'Este decorated one of the first *studios* consecrated to the Muses (in memory, certainly, of the *museion* of Alexandria, Alexandria, Egypt). We tend to forget how the alchemical and ringing preciousness of the colors used by Cosmé Tura to paint his *Terrible idol of Borneo*—that is, the *Muse* of the National Gallery in London—was functional to that mysterious, silent, humanistically shadowy dimension that was typical of the *museum* [4]. In 1497, Sabadino degli Arienti must have been referring to such a small, collected environment, using not incidentally the term *camerino*, which was destined to great sixteenth-century fortune, especially in the Este circles [5].

Renaissance *studioli*, or *camerini*, conceived as private rooms for study and reflection in the great stately palaces of the 15th and 16th centuries, contained riches and artistic heritage of inestimable value. However, over the centuries, most of these spaces, desired by the most influential personalities of the Renaissance era, were dismantled, causing the dispersion of valuable furnishings and, in some cases, the re-furnishing of rooms. These events have made the *studioli* an object of great fascination for scholars of art history who, for decades, have devoted themselves to reconstructing the intricate vicissitudes of these rooms and the artifacts they contained.

The analysis of *camerini* is not only a specific subject of study but also extremely relevant, as it allows us to re-examine the entire course of museum constructions, discovering their origins, following their evolution, and critically reassessing their current character. Since the early 2000s, several Italian *studioli* have been reconstructed as 3D digital models, with different levels of detail and precision. These projects allowed us to understand the original appearance of these striking spaces, making them accessible not only through academic studies but also through innovative experiences. However, a specific and systematic methodology of reconstruction has never been developed. For this reason, the aim of this paper is to present a specific methodology for the reconstruction of *camerini* and their visualization with high visual quality to provide art historians, curators, institutions, and visitors with a comprehensive set of procedures to follow to obtain an accurate reconstruction of this architectural type.

This manuscript also discusses the issue of virtual restitution of the architectural structure with a view of the relocation of artistic artifacts. The main objective of the "Dark Vision Experience" project, the research that led to the development of the method presented, is to highlight the importance of lighting and, consequently, the quality of night vision by the light of ancient oil lamps, whose splendid glow allowed for proper appreciation of the material and stylistic qualities of the paintings belonging to different pictorial schools.

To define the procedure, three different points of view are combined in a common methodological approach: that of the art historian (the expert in the history of the design, construction, and evolution of buildings), that of the surveyor (the expert in the construction of realistic 3D models), and that of the designer (who wants to know the past and present state of the artifact in order to design its future).

The method was developed starting from a well-known case study: the Ippolito d'Este's *camerino* in Tivoli. One of the authors of this paper had reconstructed the furnishings of one of the *camerini* located on the high floor, above the *piano nobile*, inside the Este palace in Tivoli, based on a careful examination conducted several years ago on the patrimonial inventories drawn up on several occasions between 1535 and 1572 [6].

In detail, this article, after a description of the state of the art in *camerini* reconstruction, aims to show the main issues related to this specific space. To solve the surveyed problems, the developed method is illustrated, focusing on both the explanation of reconstructive sources and the geometric and material survey of spaces and elements. Then, the case study is introduced, followed by a detailed description of the problems addressed and solutions found. Finally, the results are presented, in particular concerning the analysis of the scene optimization process based on perception, which is a key step in the developed workflow (Figure 1).

Figure 1. The *Quarto Camerino* in Villa Este in Tivoli as it was reconstructed following the method illustrated in this paper.

2. The State of the Art

2.1. The State of the Art in the Camerini Reconstruction

The state of the art in the 3D reconstruction of the *camerini* will be described starting from four emblematic case studies.

a. *Federico da Montefeltro's studiolo in the Palazzo Ducale of Urbino*

One of the first cases of virtual reconstruction aimed at recovering the original forms of a *studiolo* is the *camerino* of Federico da Montefeltro, built in 1476 in the Ducal Palace of Urbino [7,8]. It is one of the most illustrious examples of a Renaissance *studiolo*, celebrated for its wooden inlays and the wealth of artistic and scientific references embodied in its decorations. To celebrate this extraordinarily valuable space, an interdisciplinary project was launched in 2008, resulting in the exhibition "Radici e sviluppo della tradizione scientifica urbinate: Federico da Montefeltro e il Gabinetto di Fisica dell'Università".

For this exhibition, the Gabinetto di Fisica of the Università degli Studi di Urbino Carlo Bo developed a 3D reconstruction that allows visitors to explore the *studiolo* in an immersive and interactive experience, moving freely in space, zooming in and observing the details of the decorations, relocated according to their original arrangement. The aim was to reconstruct the original *studiolo*, even reproducing elements that no longer exist and making them available in an interactive mode.

The reconstruction process was carried out through extensive photographic mapping with chromatically calibrated images and planimetric surveys of the s*tudiolo*. This pioneering project also included an attempt to simulate the natural light entering the s*tudiolo* through the single window. However, the attention given to the simulation of the lighting components seems to be rather limited. The lighting was fixed, the materials were modeled in color only, and the optical reflection properties of the surfaces were not reproduced. This approach could not convincingly reproduce the complex interactions between light and matter that occur in the real environment. This prevented the full artistic value of the inlaid surfaces, where the play of light and shadow could have highlighted the subtlety of lines and meticulous detail. Another consequence of this design choice is that the pictorial decorations, rich in nuances and tonal subtleties, are less sharp and vivid. In fact, static lighting reduces the perception of their three-dimensionality and volume, compromising the overall effect of depth and realism.

b. *Federico da Montefeltro's second* studiolo *in Gubbio*

Federico da Montefeltro's second *studiolo*, located in the ducal palace in Gubbio and built between 1474 and 1482, has also been the subject of a virtual reconstruction, which allowed for its wider appreciation and historical understanding [9]. The room, located on the main floor of the palace, was a small trapezoidal room with proportions like those of its counterpart in the Residence of Urbino: the longer sides measured 3.9 and 4.1 m; the shorter ones measured 2.8 and 2 m; and the ceiling, with a coffered roof, was placed at a height of about 4 m. The room was famous for the inlaid wooden panels that lined it, characterized by striking, three-dimensional visual illusions and decorated with images that symbolized Duke Frederick's erudition and interests. Above these wooden panels was placed a painted decorative apparatus, also like that of the Urbino *studiolo*, consisting of portraits of 28 illustrious men of the time. This decorative apparatus was dismantled in 1939, and a few years later the wooden panels were purchased by the Metropolitan Museum in New York, where they are now on display after a long restoration process.

The digital project launched in 2019 and curated by FrameLAB—a research laboratory of the Department of Cultural Heritage of the University of Bologna—in collaboration with the Polo Museale dell'Umbria, the Polytechnic of Turin, and the University of Perugia, aims to restore the original appearance of the *studiolo* in its historical location and, at the same time, to remedy, albeit partially, the current dispersion of its furnishings.

The result is a metrically accurate and fully navigable digital replica of the *studiolo*, conceived as a technological support to the on-site physical replica set up in 2009. In the physical room, in fact, there is a 32″ touch-screen station allowing visitors to explore, in detail and at 360°, the high-resolution video narrative of the *studiolo*. The model used by the application is the result of a digitization process articulated in several phases: the first phase of high-resolution photographic acquisition of the original inlays, carried out directly at the Metropolitan Museum, which produced chromatically correct images, and the second phase, carried out by the Department of Architecture and Design of the Polytechnic of Turin, which generated 3D surveys of the *camerino* space using laser scanning technology. This digital reconstruction, enriched with visual and sound elements, allows for the exploration of the *studiolo* according to gamification logic, allowing the user to move in the virtual space with a first-person view and to observe every detail from different angles.

Despite the wealth of information, the lighting reproduced is static and not very faithful to the original conditions of the *studiolo*, which was probably designed to be experienced in an intimate atmosphere, fostered by semi-darkness conducive to reflection and contemplation. The inlays were digitally assembled by reproducing the lighting effects closely related to the illusionistic chiaroscuro of the reliefs, carefully preserved even in the post-production phase. However, the choice of natural and diffuse lighting, generally from above, seems questionable given the absence of a window at the top of the three-dimensional space.

c. Belfiore's studiolo *in Ferrara*

The *Studiolo di Belfiore* was one of the most important rooms of the vanished Delizia di Belfiore, one of the urban and suburban residences of the Este family in the Duchy of Ferrara. Built at the end of the 14th century, the Delizia was almost destroyed by fire, but in the 15th century it was one of the most admired residences of the time.

The *studiolo* was about 54 square meters, much larger than other examples of *studioli* that still exist today (those of Federico da Montefeltro were about 18 square meters in the case of Urbino and 15 square meters in the case of Gubbio; the 16th century *studiolo* of Alfonso I d'Este measured about 24 square meters) and was lit by two large windows (1.60 m × 0.90 m). Above these were the famous paintings of the Muses, framed by wooden elements that simulated architectural frames. Despite the devastation suffered by Delizia over the centuries, including fires and military attacks, the paintings have been preserved and have now been distributed among several museums in Europe.

The Belfiore *studiolo* was the subject of a valorization project launched in 2019 as a result of collaboration between FrameLAB of the University of Bologna, the Pinacoteca Nazionale di Ferrara, and the Gallerie Estensi, focusing on digital storytelling and privileging illustration of the iconographic program and the history of the *studiolo* over a navigable three-dimensional reconstruction [10]. This choice was motivated by the lack of detailed sources on the form of the wooden inlays and the composition and placement of the original furnishings, a circumstance that could have compromised the philological accuracy of the result. The three-dimensional model of the *studiolo* that appears in the video is based on data from the Autentico dei Lavoratori, a historical document that recorded the fees and activities of the craftsmen involved in the creation of the *studiolo.* In the model, the shape of the inlays, which is not explicitly described in the sources, was reconstructed by copying other panels made by the same craftsman: Arduino da Baiso.

The wooden essences replicated in the 3D models were photo-realistically reproduced, even adding minor imperfections caused by time. The six canvases of the Muses, placed on the wall opposite the entrance, were digitized in high resolution using photogrammetry and then colorimetrically corrected to equalize their light and color balance, making the visual perception of the works homogeneous in the digital model. Despite the presence of two large ultramarine glass windows, no attempt was made to replicate the effect of natural light in the room. The lack of detailed documentation on the actual lighting configuration makes a philologically accurate reconstruction impossible. It is not possible to reliably reproduce the color and transparency of the glass panes, nor the direction and intensity of the natural light passing through them.

d. The studiolo *of Isabella d'Este in Mantua*

After her marriage to Francesco II Gonzaga in 1490, Isabella d'Este settled in the apartments on the main floor of the ducal castle of San Giorgio in Mantua. Here, she had a small, dimly lit room without a fireplace built, where she enjoyed her pastimes, studies, and correspondence. The room housed a priceless collection of books, works of art, archeological finds, and naturalistic curiosities—an impressive collection that was the pride of the Gonzaga family until it was dispersed in the seventeenth century. As a lover of music and the arts, Isabella developed a decorative program for her *studiolo* based on mythological and allegorical themes drawn from ancient literature to celebrate her family. The *studiolo* was therefore the home of several precious paintings, according to a project that aimed to "compete" different artists of the time by having them work on canvases of the same size, all with mythological themes. The works in the *studiolo*, now in the Louvre Museum, had illustrious authors, including Pietro Perugino, Andrea Mantegna, Lorenzo Costa, and Correggio. When her husband Francesco Gonzaga died in 1519, Isabella moved to the widow's apartment in another wing of the Mantua castle. Because of this move, the *camerino*/*studiolo* and the adjoining room, known as *La Grotta*, were dismantled and reassembled in new rooms located in the Marquise's second apartment.

After Isabella's death, the *studiolo* was abandoned, and the paintings were sold. Today, therefore, the *studiolo* and the *grotta* are still structurally intact, but the heritage they contain has been dispersed, and the original appearance of these rooms has been lost.

The IDEA (Isabella d'Este Archive) project, an academic initiative designed to study the Italian Renaissance through the figure of Isabella, has breathed new life into these two precious rooms. It is a research project that takes an interdisciplinary approach, combining 3D modeling technologies with textual analysis and philological research to virtually reconstruct every aspect of Isabella's life and collections [11]. The result is a complex digital platform, hosted online and fully accessible, that brings together information and documents about the Marquise's correspondence and legacy, digitally reconstructed through virtual and augmented reality. All reconstructions will be accompanied by accurate analysis based on historical documents, such as inventories and correspondence, to accurately represent the cultural and artistic environment of the time. The project therefore aims not only to preserve and make accessible the materials but also to stimulate new research and provide immersive experiences that connect modern audiences with the historical past.

The reconstruction of the *studiolo* and Isabella's *grotta* is the result of a process combining several digital modeling and visualization techniques, ensuring a high level of historical fidelity and realism. Acquisition of the existing space was accomplished by photogrammetry, a technique that allowed for precise measurements of the physical space. The resulting web application can be accessed via browser and allows visitors to explore the *studiolo* and the *grotta* through three different modes of navigation: first-person, third-person, in which the camera orbits an avatar representing Isabella d'Este, and close-up, allowing them to draw nearer to the objects to observe their details and access a catalog of in-depth information about the works present, such as dimensions, inventories, and bibliographical references.

Despite the accuracy and level of detail achieved by this reconstruction, there emerges a lack of clear architectural semantics that prevents the association of 2D analysis with semantically geolocated 3D and the simulation of night light, which probably represented the most frequently experienced lighting condition in the *studiolo*. The integration of such elements would further enrich the immersive experience, offering a more complete understanding of the original atmosphere of the place.

Summing up, all of the projects described were carried out according to a multidisciplinary approach that integrated scientific documentation methods and technological tools, demonstrating how the mixture of modeling techniques and digital visualization can restore new life to lost spaces. However, for better compliance with historical truth, aspects such as semantic modeling, the explicit stating of reconstructive sources and their reliability for each part, methods of surveying, replication of the optical reflection properties of materials, and the study of the effect of light must be carefully considered.

2.2. The State of the Art in Architectural Historical Reconstruction

In recent years, an extensive body of literature was produced concerning the topic of the virtual reconstruction of historical buildings that can be easily, and without any lack of information, adapted to interior spaces and then also to the *camerini* [12–16].

This section reviews and analyzes these and related studies, focusing on two main different topics concerning the following 3D model quality criteria:

- Historical reconstruction source reliability;
- Geometric and photometric behaviors.

2.2.1. Historical Reconstruction Source Reliability: 3D Model Quality Criteria

In the last decade, reconstructive hypotheses of buildings in a state of ruin or significantly altered by time and events since their construction, unbuilt or disappeared, have been the subject of extensive studies [17]. The aim is to broadly distinguish between the function of the 3D model as a purely illustrative type and a 3D model for scientific purposes, i.e., a medium capable of properly understanding an ancient building (existing or not), its function, use, etc., and specifically to systematize and ensure the transparency of the information collected and processed to create digital models that are accurate and adhere to the original with varying degrees of reliability [18].

Over the years, various authors have proposed different solutions for conceptualizing and visualizing reconstructive hypotheses, introducing numerous concepts essential for accurate 3D reconstruction. Among these, the level of reliability (LOR) [19] assigned to every piece of evidence is crucial, as it determines the confidence in the data used for reconstruction. This concept ensures that each piece of evidence is evaluated for its authenticity and relevance, providing a foundation for the reconstruction process. Another significant concept is temporal uncertainty across multiple sets of data with diverse dating [20]. This addresses the challenges of integrating data from different time periods and sources, acknowledging the inherent uncertainties in dating and temporal alignment. By considering temporal uncertainty, reconstructions can more accurately reflect the historical context and changes over time.

Other authors have introduced additional terms to further refine the conceptual framework for 3D reconstructions [21]. E.g., the level of existence (LOE) is a concept that categorizes the degree to which different elements of a reconstruction are supported by evidence. This helps in distinguishing between well-documented features and those that are more speculative, ensuring transparency in the reconstruction process. Similarly, the Level of Geometrical Reliability (LOGR) assesses the accuracy of the geometric representation of reconstructed elements. This metric is vital for ensuring that the spatial dimensions and relationships within the reconstruction are as precise as possible, based on the available evidence. The Index of Reliability (IR) is another important concept, providing a quantitative measure of the overall reliability of the reconstruction. This index combines various factors, including the quality of evidence, temporal uncertainty, and geometrical accuracy, to give a comprehensive assessment of the reconstruction's credibility.

These concepts are complemented by the development of a graphical code capable of visually conveying the certainty of reconstructive elements through probability maps and the historical/archaeological evidence scale [22]. Several scholars have theorized about the use of a semantic structure in digital modeling as a potential way to facilitate the reading and understanding of the reconstructive hypothesis.

The Extended Matrix (EM), developed by CNR-ISPC in Rome [23], is a formal language designed to trace virtual reconstruction processes. This tool is used by archeologists and cultural heritage specialists to robustly document their scientific activities. EM employs a node-based language and represents certainty by means of standardized colors—a sort of evidence scale based on the binary concept of existing or absent documentary units. The color code has the following meaning:

1. Red: I am sure it exists because it is preserved;
2. Orange: I am sure it existed because there is documentation about it;
3. Blue: I am sure something existed, but I only know partial properties;
4. Yellow: I am sure it existed, but I am not sure about its original position;
5. Dark yellow: I am sure something existed, but I am not sure about its original position;

6. Green: I believe it existed. My reconstruction is not based on in situ elements (all those parts for which we have no structural or archeological evidence, but their reconstruction is entrusted to comparisons or interpreted sources).

Aparicio and Figueiredo [24] propose a system for organizing the virtual reconstruction of ancient buildings based on Reconstructive Units (RUs) and a scale of historical/archeological evidence. RUs refer to discrete components of a building that can be reconstructed individually based on available evidence, namely kinds of reconstruction semantics. The scale of historical/archeological evidence evaluates the degree of certainty of each reconstruction, ranging from speculative to highly reliable. This framework allows for a more systematic and transparent approach to virtual reconstructions, ensuring that they are based on varying levels of archeological data and historical understanding.

This method has been successfully employed in high-value archeological research [25], demonstrating its effectiveness in ensuring accurate and well-documented reconstructions. However, it can also be applied as a general criterion for interpretation and organization of work in other fields, such as the study of Renaissance *camerini*. By adapting the principles of RUs and the evidence scale, this approach can provide concepts and tools for a robust framework for 3D reconstruction, ensuring that the hypotheses acknowledged are not only visually accurate but also scientifically credible and transparent. As a matter of fact, RUs are easily implementable, even in interiors for exhibition purposes. In the broader context of semantics, they produce a hierarchy of models, making validation more straightforward and elementary. We improved these methods by customizing them for the case of *camerini* and incorporating perceptual criteria motivated by the use of these spaces, i.e., rooms designed for observing artworks in their true aesthetic context. However, it appears that an important perceptual dimension is lacking in this line of research, which is primarily based on RUs and the scale of historical/archeological evidence. Specifically, the reliability of a 3D reconstruction of an ancient building is not a general criterion but rather depends on the proximity of the observer to the individual RU. This aspect has been developed as an original contribution to the broader discourse on the credibility of 3D reconstructions in archeological studies.

2.2.2. Geometric and Radiometric 3D Model Quality Criteria

From the bibliographic review, e.g., in [17], several implementable solutions emerge as applicable to the workflow involved in the reconstruction of Renaissance *camerini*.

For currently standing buildings with historic interiors that no longer exist, it is recommended to begin with reliable 3D surveys to create digital models that accurately reflect reality [12]. This method helps to address the persistent issue of relying on less reliable solutions based on outdated and unverified two-dimensional drawings.

The second aspect is the transparency and integration of the information that leads to the realization of a specific reconstructive solution. To effectively integrate information derived from literary sources, historical images, or plans and elevations representing the state of a room at a specific moment, the most effective solution is a semantic subdivision of the 3D model. In this approach, each granular element is associated with a specific reliability assessment.

A key aspect of the process involved in generating individual RUs is their origin. In this context, the reconstructions are primarily grounded in reality-based data, ensuring a robust and accurate foundation for further modeling development. If a building is well preserved, it is possible to digitize parts of it that are compatible with a space that no longer exists. Active and passive sensors can also be used to document its shape, color, and other properties useful for virtual reconstruction. When specific information is not available, it is necessary to use direct modeling and texturing techniques. In such cases, generic textures are used to represent the appearance of the building. However, the practice of using such 2D assets from collections or repositories without any spatialization of the contents is not advisable, as they produce effects that are difficult to verify through standardized evaluation processes [26]. However, it is important to note that the use of such techniques, particularly for elements or the entire "envelope" of the room, significantly reduces the quality of the reconstruction.

In the contemporary panorama of 3D modeling for enhanced interaction, various approaches can be utilized for the reconstruction of historical interiors and works of art. These techniques leverage data obtained through laser scanning and photogrammetry, each supported by a growing body of research [27–30].

In general, a crucial role is played by the approach to scene optimization, and several possibilities can be put into practice—using smart decimation by means of triangles, isotropic quadrilateral meshes (quad-remeshing), or through manual polygonal modeling operations or retopology [31,32].

These techniques are recommended at the final stage of geometric reconstruction from reality-based data. This step, although not always mentioned in the scientific literature, allows for better management of geometries and the optical reflectance of materials inferred in the geometric model. Optimized parametrization provides high control of the geometry and model mapping, especially for textures that contribute to the realistic simulation of less common materials, as opposed to the widely used Lambertian approximations in architecture. Additionally, this technique can be used when reconstructing interior spaces from scratch.

Another main topic concerns the reproduction of the physical reflection properties of the materials that make up the surfaces of the interior space (floor, ceiling, walls, and transparent surfaces, such as windows and decorations). In this sense, the scientific literature appears much less abundant and generally more focused on the integration of different models within original environments without emphasizing the complete light–material interaction enabled by contemporary computer graphics (CGs) [33,34]. However, when working within the fields of art and architectural history, the chromatic, material, and lighting aspects of artworks and environments are, and should be, essential for the proper use of 3D reconstructions for scientific purposes. There are indeed examples of 3D reconstructions that pay careful attention to the reconstruction of materials and textures of surfaces of the room [35,36], but they are quantitatively fewer than the number of studies on 3D reconstructions at the architectural scale (general external views, perspectives, and axonometric cutaways) and the urban scale. In other words, reconstructions that integrate both architectural interiors and the "microscale" perception of artworks highlight a significant gap in the current scientific literature.

Based on the studies analyzed, it is evident that there is a need to develop a working method that achieves complete realism in 3D reconstruction solutions for interiors and exhibited artworks. This method should advance the integration of philological studies, ensure meticulous data capture and management of architectures and artworks, and, importantly, fully exploit the visualization capabilities afforded by the current state of the art in physically accurate visualization technologies.

3. Case Study

Ippolito d'Este's *Quarto Camerino*, located on the top floor of the Este Palace in Tivoli, is a perfect example of Renaissance humanistic culture, where art, knowledge, and power were intertwined in an intimate yet sumptuous space. Like all Renaissance *studioli*, it was not only a place of contemplation and personal retreat but also a visible manifestation of the cultural and political prestige of its owner.

Thanks to the patrimonial inventories (1535–1572), it has been possible to reconstruct, at least in part, the richness and peculiarity of this room, despite the subsequent refunctionalization that changed its original purpose. The walls were covered with fine *corami* and decorated with works of immense value attributed to masters such as Titian, Raphael, Jacopo Palma, and François Clouet. These paintings, now preserved in various museums, bear witness not only to Ippolito's aesthetic taste but also to the Este family's desire to demonstrate their role as patrons and promoters of culture.

The *camerino* was thus a microcosm of the Renaissance, conceived as a treasure chest of knowledge, aesthetics, and power, reflecting a tradition that made the atelier a place charged with symbolic meaning. In addition to being functional spaces, they were tangible representations of the cultural and political identity of their owners, in this case one of the most illustrious members of the Estense family.

4. Method Developed

In this section, the criteria and general methods aimed at the realization of the *camerini* reconstruction for research purposes will be explained. These are derived from the development of existing working protocols, which have been customized and enriched with innovative elements (Figure 2). Furthermore, these general criteria come from the representative case study illustrated in Section 3. It well represents all the problems that can be encountered in a reconstruction of this type of room space: textual sources only, uncertain location, the current state in which original surfaces (floors, walls, ceilings) are unrecognizable, and the lack of information on the specific location of each artwork. Ultimately, the traditional procedure of ex-post evaluation of the result obtained (validation) was not followed. An ex-ante approach was preferred, in which each decision was made a priori based on a path with multiple collaborative working groups involving various skills.

Figure 2. View of the reconstructive model with a scale depicting historical evidence. Colors applied to each RU correspond to a different amount of evidence.

4.1. Gathering and Interpretation of Sources

The reconstruction of a no-longer-existing *camerino* is a topic that must be divided into smaller problems. The developed method is depicted in Figures 3 and 4, showing both the conceptual and technical workflows allowing for the hypothetical reconstruction.

The adopted strategy is entirely focused on the use of materials derived from the study of examples consistent with the sources chosen (conjecture based on similar structures).

On the one hand, we must elaborate on written sources (primary, secondary, and tertiary), the available iconographic apparatus, and current graphic documentation. The objective of this is to establish a set of general and specific typological features for the case under examination that can together provide an abacus of elements of varying reliability that can be used in the reconstruction process.

On the other hand, we have the practical aspect of digitizing elements deemed compatible with the environment that we propose to reconstruct virtually in every detail. This digitization is carried out extensively with the aim of producing a dimensional and formal reference allowing for us to understand the position and structure of the interior to be reconstructed. The digitization will take place using techniques able to facilitate the integration of various parts (individual constructive elements, cladding, finishes, movable elements). In the established workflow, we intentionally avoid the use of standardized materials in order to guarantee the authenticity and homogeneity of sources.

Based on the initial study phase, we proceed with the systematic documentation of the building's structure, or part of it, to obtain a complete updated synoptic of the elements of the building that housed the *Camerino*.

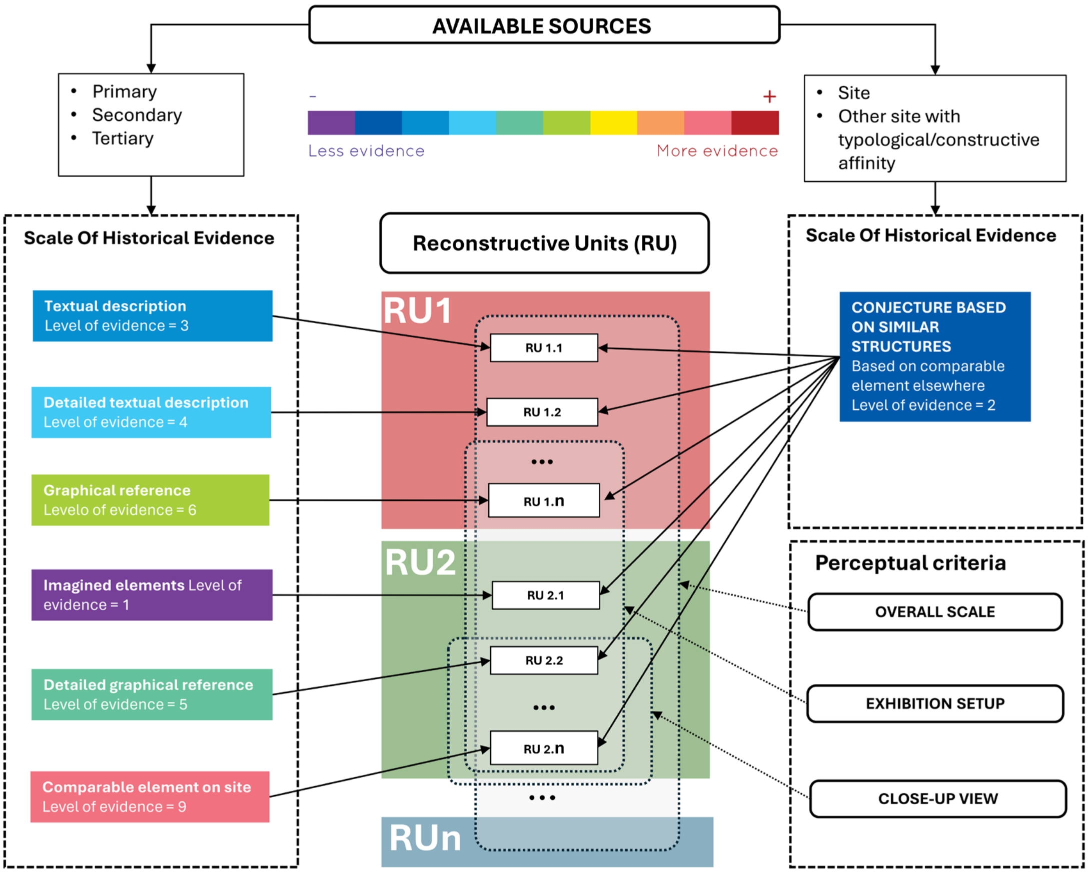

Figure 3. General diagram of the developed workflow in which the integration between sources and reality-based models to generate the individual RU is shown. Added to this process of transparency is a perceptual criterion of proximity to the RUs.

All information available for reconstruction is homogenized and grouped into a series of reconstruction units (RUs) representing different states of historical evidence (Scale of Historical Evidence) (Figure 3). RUs are hierarchically organized following perceptual criteria that depend on the objective importance of the element, its lighting, and the modes of exploration of the virtual environment by the observers (subjective importance). E.g., for the objective criteria, the artworks and the walls are of primary interest since the lighting of the *camerini* was designed to emphasize the artwork and its background, i.e., the exhibition, while other surfaces (floors and ceilings) were on a lower hierarchical level.

We focus on the objectives' criteria. In the method we propose, we do not seek a solution that provides a global parameter of reliability, but rather we aim for a quantification of reliability that varies depending on the observer's level of proximity to a semantically organized structure. Since interiors are perceived from a mobile point of view, even during the artwork's observation, following the natural inclination of the visitor towards points of interest evaluated spontaneously, reliability is designed as a function of movement and the degree of proximity to individual RUs, making the evaluation a constantly updatable process. Perceived images are then grouped into three categories of different proximity: overall scale, exhibition setup, close-up view (see paragraph 4.3).

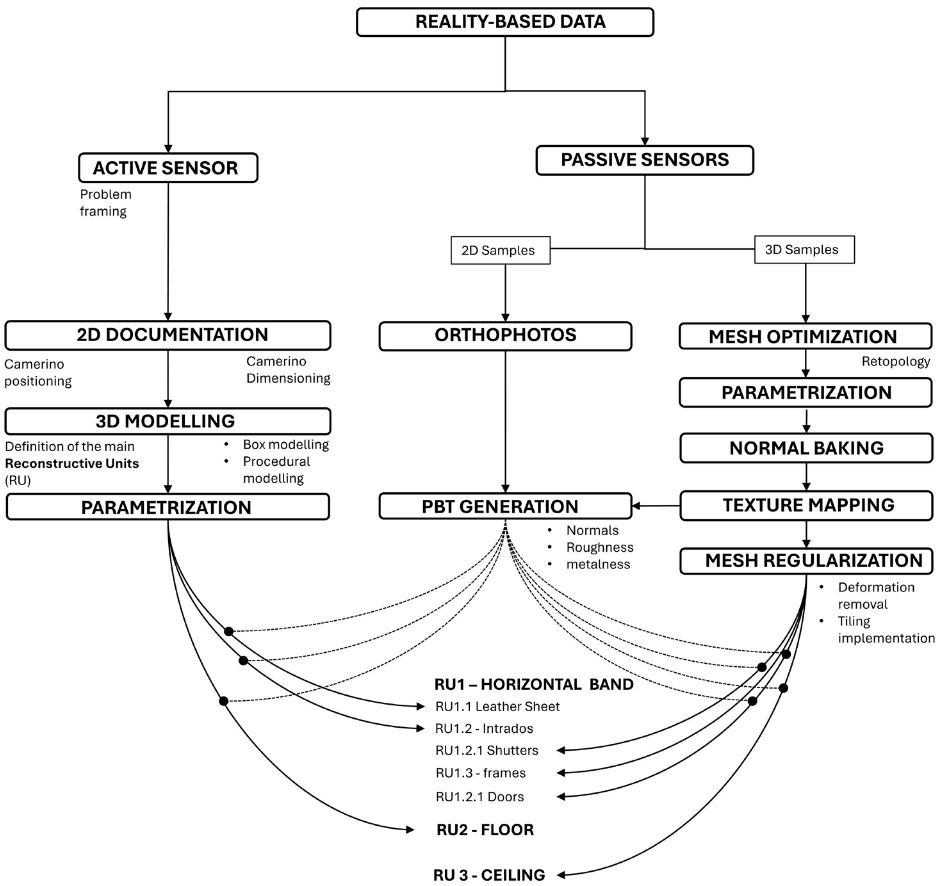

Figure 4. Diagram summarizing the production process of individual RUs in terms of CG techniques employed. An active sensor and 3D modeling techniques are used to define the volume. Photogrammetry is used to obtain 3D details and physically based textures (PBTs). The hierarchical structure of the RUs is based on semantic organization.

4.2. Integration of 3D Assets Inside the RUs

The workflow developed for the reconstruction includes three types of assets:

- The *camerino* bounding box and the system of accesses and windows that allow for its function (volume);
- The individual assets (details);
- The chromatic and material aspects of the surfaces (textures).

The first part of the reconstructive process is based on a standard workflow (active digitization and extraction of the main sections), which allows for the creation of the three-dimensional "framework". Such volume is detailed and articulated with the contribution of 3D assets and textures derived from photogrammetric pipelines. The diagram in Figure 4 illustrates the sources of the assets; i.e., the combined use of active and passive sensors is summarized.

Surveyed and reconstructed data are then simplified and organized through a semantic subdivision of the internal environment, which will facilitate the integration of digital models from heterogeneous sources (direct modeling, passive and active sensors).

The strategy for the reassembling of the different parts is based on the subdivision of the *camerino* into three main parts, each endowed with specific functional and structural features: the horizontal band (i.e., walls and openings), floor, and ceiling. Given the exhibition nature—namely, a space designed to host and display artworks to be perceived visually—the most important area of the architectural container is the horizontal band of the "masonry box", which constitutes the perceptual horizon of the virtual visitor (Figure 5a). The architect and the client would have carefully planned the relationship between the *système des objects* (the collection) and the background, that is, the walls on which to hang paintings and the plastic works that will cast their shadows on them. The second conceptual division of the enclosure housing the collection is the floor, which serves as the two-dimensional constraint for movement during the virtual visit (Figure 5b). The enclosure also features a third part, the intrados of the ceiling, which constitutes the conceptual termination of the interior architectural system (Figure 5c).

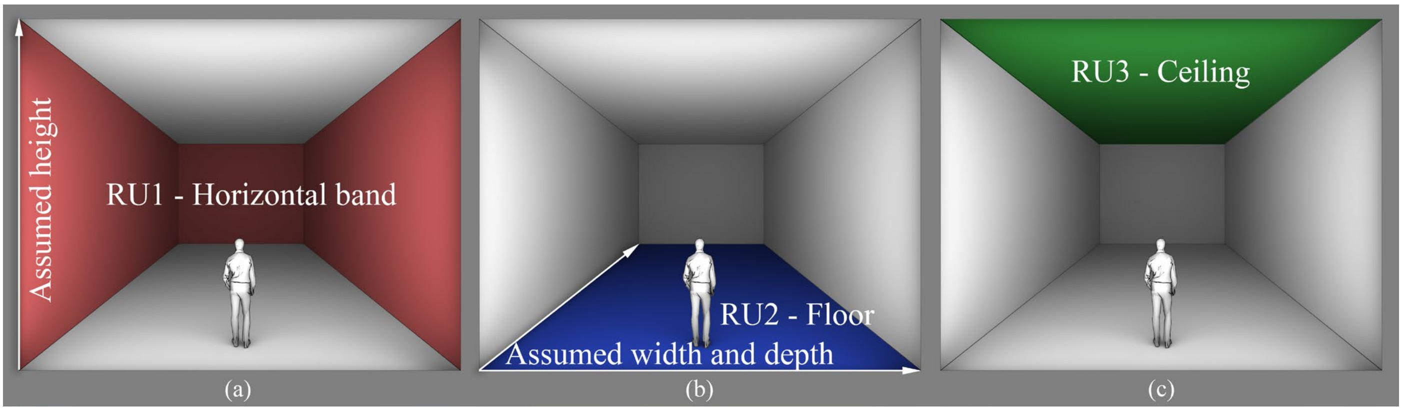

Figure 5. Reconstructive Units (RUs) or macro semantics of the cabinet in relation to the exhibition function. (**a**) 'RU1 - Horizontal band' constitutes the backdrop for the exhibited works and assumes a high value in the reconstructive process, (**b**) 'RU2 - Floor' constitutes the constraint for the observer's movements, (**c**) 'RU3 - Ceiling' is the conceptual and physical termination that encloses the entire system.

In this strategy of semantic organization, a very simplified geometry of the *camerino* is used because each part will function as a proxy to be detailed using photogrammetric models in a series of successive phases and comparisons within the working group.

Once the semantics of the internal space are defined, four in-depth processes are to be carried out to deepen and detail the reconstruction, listed as follows:

- The *camerino* bounding box: The simplified 3D reconstruction of the *camerino* is based on the extraction of 2D schematic drawings from the point cloud. Horizontal and vertical sections together form the basis for creating simplified volume (bounding box). Once simple modeling operations have been performed (extrusion, Boolean operations), a semantic organization of the geometry is necessary to ensure that the simplified geometry is split into parts consistently with Reconstructive Units (RU). It is important to recognize that each RU will need to be either replaced, integrated, or used as a template for mapping operations. Indeed, each part, working as a proxy, is detailed using photogrammetric models.

- Individual assets: The first aspect is related to the topological regularity of each RU. Models to be experienced need, on the one hand, severe optimization to facilitate the faithful reproduction of details, easy management of variants, and new features. On the other hand, RU optimization facilitates the reproduction of optical reflection properties of the surfaces, namely the replica of BRDF (Bidirectional Reflectance Distribution Function) behaviors [37]. Therefore, each 3D sample (Figure 3) forming part of the RUs should be low-poly and free of topological and geometric defects [38]. A special workflow is provided for reconstructing architectural elements using references from the same building or other buildings, e.g., window frames and shutters (both movable), wooden doors, ceilings, and cornices. These elements should be interactively adaptable to a range of dimensional modifications to ensure compatibility with the hypotheses evaluated by the interdisciplinary team and to the reconstructed architectural space. Regarding the reconstruction of the wall coverings (usually patterned), to achieve maximum control over tiling, it was preferred to avoid the classic solution based on texture projection and automatic repetition along the horizontal and vertical sides of the individual walls. A procedural system based on Visual Programming Language (VPL) [39] was chosen, which creates arrays where the basic element is the single piece of wallpaper (Figure 6). The individual walls are automatically filled with rectangular sheets, previously parametrized with the texture set that reproduces the complex optical behavior of these elements, which are highly characteristic of the *camerino/studiolo*. The advantage of working with the digital equivalent of a single covering sheet allows for high control over tiling and the ability to introduce geometric alterations at will, mitigating the artificial effect of repeating the single element.
- The chromatic and material aspects of the surfaces: color textures or albedo (2D samples), from which maps for physically based texturing (PBT) are extracted from photogrammetric images (Figure 4). Specifically, because CG replicas of object properties are based on multitexture techniques today [40], an adequate number of pixels is provided in relation to the parametrized area to maintain constant texel density across the entire system of assets introduced in the reconstruction. Finally, a "principled"-type BRDF model is employed for an accurate simulation of various material properties [41]. The principled BRDF model combines multiple layers into a single, easy-to-use node that can model a wide variety of materials. It is based on the OpenPBR Surface shading model and provides parameters compatible with similar PBR shaders found in other software, e.g., the Disney and Standard Surface models [42].

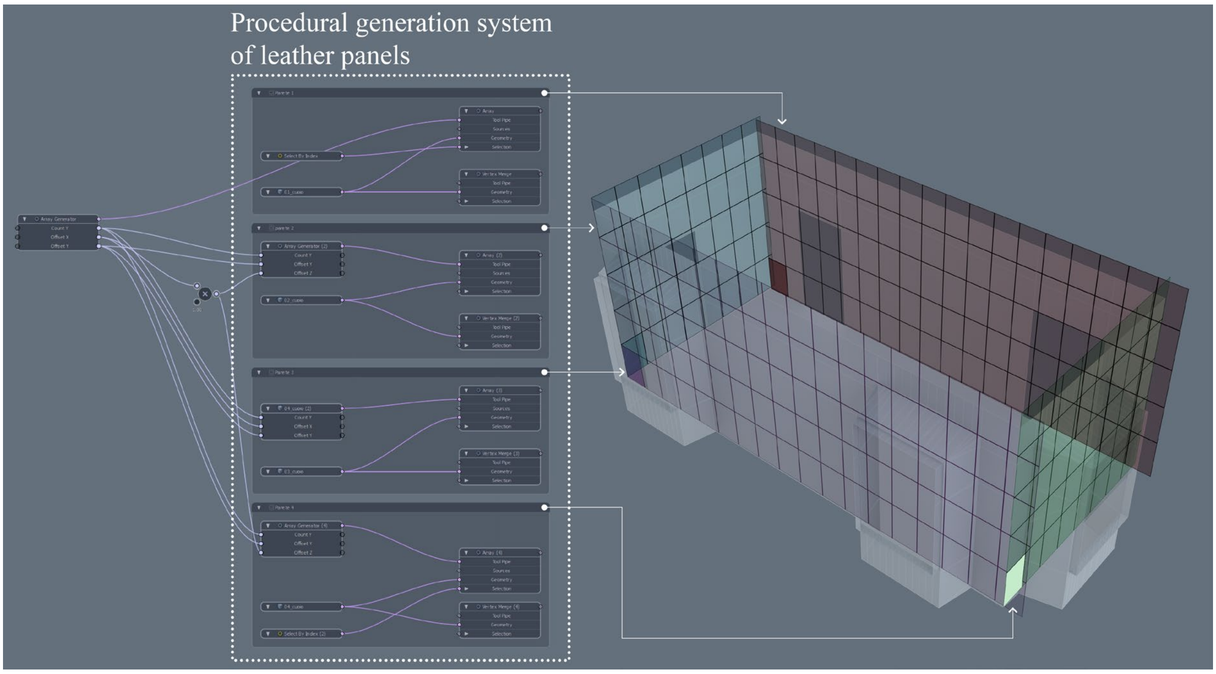

Figure 6. Procedural system based on Visual Programming Language (VPL).

4.3. Criteria for the Analysis of Perceptual Optimization

Based on these premises, and considering that the goal of reconstruction is to enable the perception of an environment, a process of analysis and refinement based on perceptual criteria at different scales was applied to the reconstructed system by the consensus group. This ensures that interactive visualization can develop new keys to understanding and further elements of verification and interpretation. Different degrees of proximity to the digital model will correspond to varying levels of reconstruction reliability. At the same time, different proximities to the model will correspond to varying levels of apparent detail. At each scale of perception, appropriate balance must be found between elements obtained through active and passive sensors and those obtained through direct geometric modeling. The scales of perception range from the general architectural interior or Overall Scale (OS) to the Exhibition Setup (ES, focused on the relationship between the collection and the background) and the Close-Up (CU) view of individual artworks (submillimetric details).

Let us now define, through general quantification, what is meant by the scale of perception in the case of the reconstruction of environments such as Tivoli's *camerino*. We have an Overall Scale (OS) that corresponds to the view of the interior space from an observation point located at a distance (D_{os}) from the internal surfaces of the *camerino*, less than or equal to the maximum dimensions that define the bounding box of the digital model (Figure 7a).

$$D_{os} \leq \max{(a, b, c)} \tag{1}$$

where *a*, *b*, and *c* are the sides of the bounding box.

The Exhibition Setup Distance (D_{es}) will be between the distance Dos and the distance from the artwork defined by the bounding box of the artwork itself, which is the maximum of the three dimensions that define it *(a′, b′, c′)*. The scale of the exhibition is such that it allows for the simultaneous visualization of the artwork as a whole and its immediate surroundings without focusing on details (Figure 7b).

$$D_{os} \leq D_{es} \leq \max{(a', b', c')} \tag{2}$$

The Close-Up distance (D_{cu}) is the near view of the artwork, which will be between the "Des" and the smallest of the dimensions that define the artwork's bounding box. In the case of a painting, this measurement may coincide with the thickness of the frame (Figure 7c). Therefore, denoting the dimensions of the artwork's bounding box as a'', b'', and c'', we have the following:

$$D_{es} \leq D_{ecu} \leq \min\,(a'', b'', c'') \tag{3}$$

The evaluation of a reconstructed environment is carried out on single frames corresponding to viewing distances. Each perceptual scale transition (from *Dos* to *Dcu*) corresponds to a rendered image that can be segmented into (n) parts corresponding to projected Reconstructive Units (RUs) on the "canvas". Then, we quantify the area in pixels for every RU and the corresponding Historical Evidence Scale. Evidence (E) of each frame, expressed as a percentage, is then evaluated on the basis of the following formula:

$$E = \frac{\sum_{i=1}^{n}(A_i \times R_i)}{\sum_{i=1}^{n} A_i} \times 10 \tag{4}$$

where A_i is the area of the segment (i) in pixels; R_i is the reliability value of segment (i) (from 1 to 10); and n is the total number of segments.

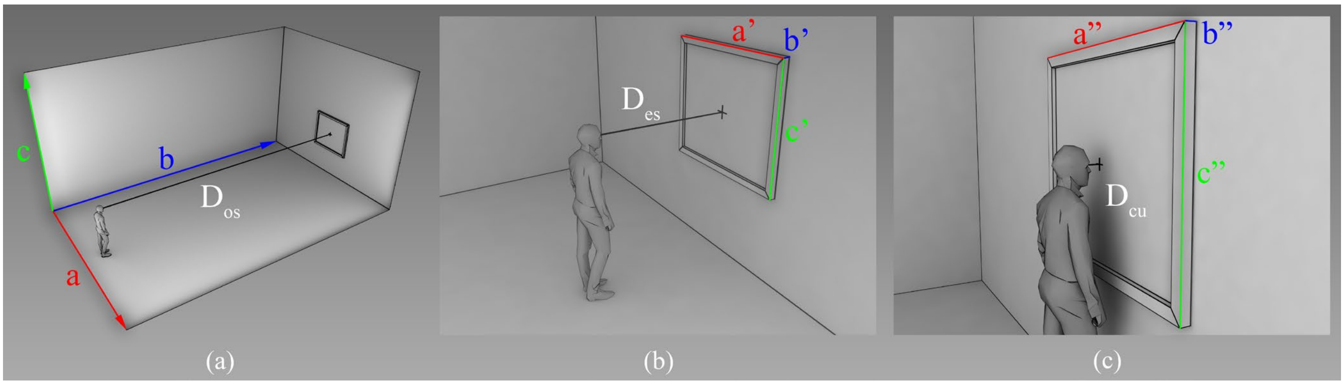

Figure 7. Viewing distances in the reconstruction. (**a**) edges *a*, *b*, and *c* are the main parameters for defining the bounding box and D_{os} is the distance between the observer and the artwork. As the observer approaches D_{os} decreases and takes on other names: D_{es}, D_{cu} as illustrated in (**b**) and (**c**). As the work is approached, other parameters relating to the dimensions of the painting and its frame are introduced a',b',c' and a'',b'',c''.

With this approach, it is possible, within an interdisciplinary group, to quantify the reliability of the reconstruction based on the virtual visit path undertaken and consequently recalibrate the detail of the various RUs. Additionally, it allows for the transparency of the reconstruction process to be made explicit to the non-expert user. The value E, being expressed as a percentage, provides quantification of the adherence of the visit to the original state of the *camerino*, as will be demonstrated in the final section of this paper (final images).

5. Results

Our 3D reconstruction of Ippolito d'Este's *Quarto Camerino* is based on the following operations:

- Finding the *Quarto Camerino* within Villa d'Este, starting from the description of the goods in the *Inventarium bonorum bonae memoriae Hippoliti Estensis Cardinalis de Ferrara*, Roma, 2 dicembre 1572, Archivio di Stato di Roma, Notai del tribunale A. C., notaio Fausto Pirolo, vol. 6039,cc. 344r-387r. [6] through a joint visit to the site by all the professionals involved (in addition to the authors, the officials of Istituto Villa Adriana and Villa d'Este);

- Checking the current consistency of spaces, finding all spatial documentation related to them, measuring them, and analyzing transformations over time;
- Reconstruction of the current state based on the elements still present and reconstruction of the missing elements based on their degree of reliability;
- Geometric reconstruction;
- CG reconstruction of surface properties;
- Analysis of the perceptual optimization;
- Lighting simulation.

We will focus on the most relevant steps and technical solution adopted, listed in detail as follows:

a., b. The northwest corner of the palace, on the second level of the building, has been identified by its planimetric dimensions as a probable reference for creating a reconstructive plan of the *Quarto Camerino* (Figure 8). However, this space should be located on the upper floor, characterized by a ceiling height lower than that of the gallery below. Based on these considerations, a plan view and a schematic elevation have been developed to be used for the subsequent survey and interpretative steps necessary for the reconstruction.

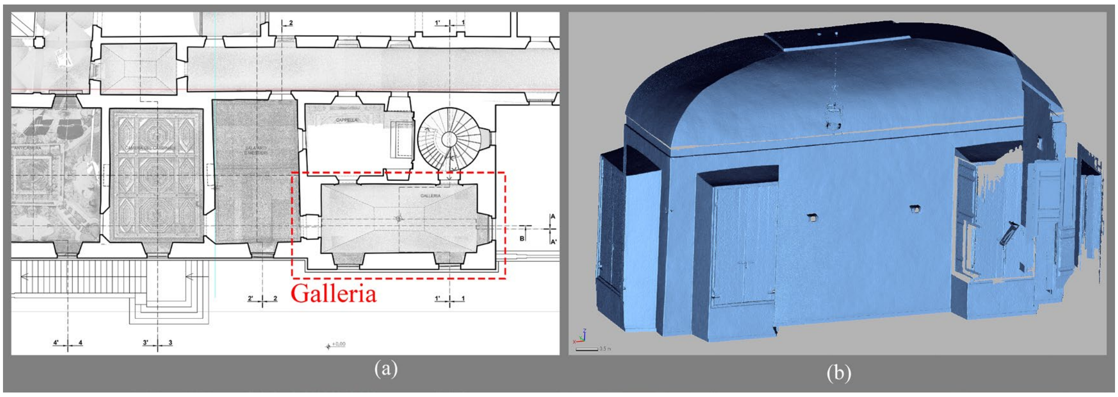

Figure 8. (**a**) The *Galleria*: a probable reference to create a reconstructive plan view. (**b**) perspective section of the *Galleria*.

c. The reconstructive operation of the *camerino* is the product of a process of gathering information and translating it into a series of hierarchical and coherent RUs structured according to the sources. The lack of iconographic sources required a search within Villa d'Este for a series of samples that were morphologically and materially analogous to those of the lost *Quarto Camerino*. The leather wall coverings, on the other hand, are the result of reworking similar modular panels found in Palazzo Chigi in Ariccia. The terracotta floor and the wooden ceiling are the result of adaptations from reconstructed or partially original spaces of Villa d'Este (Figure 9).

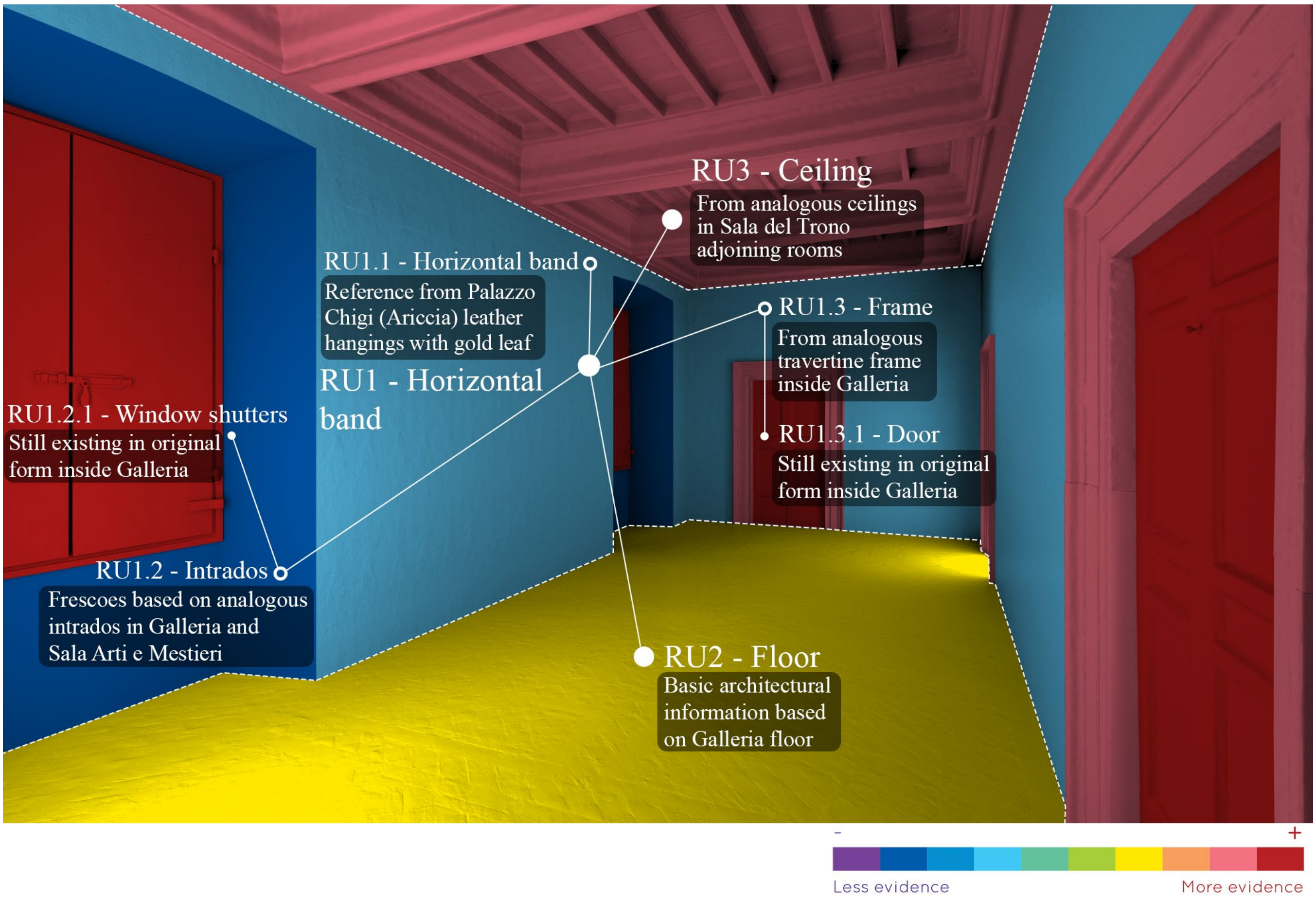

Figure 9. The model of the *Quarto Camerino* with the scale depicting historical evidence and, as labels, the sources used for the reconstruction.

Since the intrados of the *Galleria* is covered by a cloister vault and not by a low ceiling with exposed wooden beams, a common feature of Renaissance *camerini,* we identified a possible example within the remaining rooms of the same floor in Villa d'Este. Similarly, it was necessary to create a series of models (RUs) that, in accordance with the reconstructive layout and elevation (general consistency), could articulate and specify in detail the various elements of the cabinet, namely a higher level of granularity [43] (Figure 10). The horizontal band consists of a series of discontinuities such as windows with their respective frames and the passage openings between rooms, characterized by travertine frames. Finally, an additional level of semantic detail is provided by the movable parts, such as the window frames and shutters (both movable), and the wooden doors.

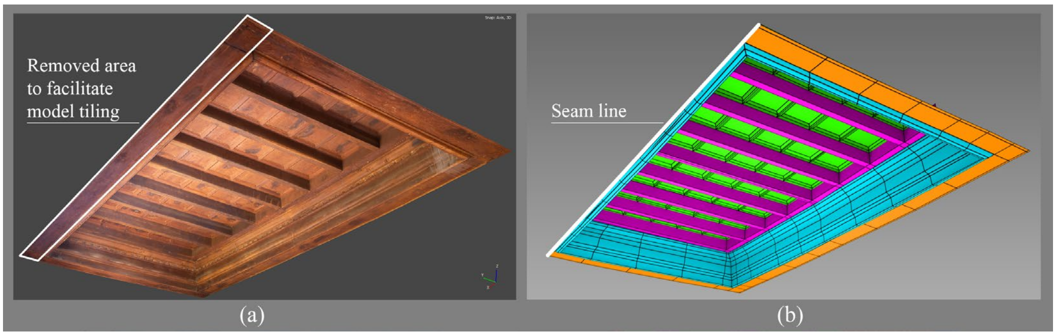

Figure 10. (**a**) Photogrammetric model of a wooden ceiling consistent with that of the *Quarto Camerino*. (**b**) simplified model.

d. Geometric reconstruction: From a technical point of view, 3D reconstruction of Ippolito d'Este's *Quarto Camerino* is based on a dual survey approach: a comprehensive measurement using an active sensor and a series of detailed photogrammetric surveys of architectural decoration elements, surface finishes, and movable elements (doors, shutters, etc.). A Terrestrial Laser Scanner (TLS) with a Leica ScanStation C5 based on Time-of-Flight (ToF) technology was used to create the 3D model of the series of rooms placed on the floor below the *camerino* (the second floor of the Villa) (Figure 11). This acquisition allowed us to obtain the planimetric and altimetric dimensions of the Villa d'Este area corresponding to the rooms known as the *Anticamera*, the *Camera del Cardinale*, the *Sala Arti e Mestieri*, the *Cappella,* the staircase, and the *Galleria* that we selected as the best references for the room that accommodated the *Quarto Camerino.* Many elements that are no longer recognizable in the rooms that housed the *camerino* were probably very similar, such as the window casings, the door frames, the doors themselves, and the floors. The resolution of the scans is 10 mm at 10 m, resulting in an average resolution between 3 and 6 mm. The 19 scans were aligned using homologous points, which allowed for an initial registration, subsequently refined through ICP algorithms [44]. Leica Cyclone 9.0 software was used for point cloud alignment and processing. The complete model consists of 191,590,409 points, and the average resolution of the model, once subjected to the scan integration process, is 3.7 mm.

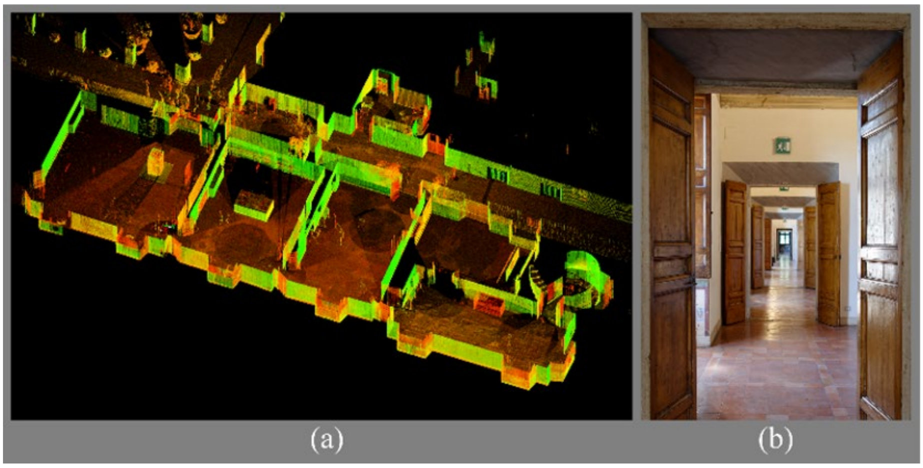

Figure 11. (**a**) Laser scanner survey of the northwest wing of the palace. (**b**) Sequence of rooms, functionally connected by a series of doors aligned along the main façade.

The photogrammetric survey, used to acquire the architectural elements in detail, was carried out by means of a Nikon D5200 Single Lens Reflex Camera equipped with a Nikon AF-P 18–55mm f.3.5-5.6 DX VR lens; an X-rite Colorchecker target was used to achieve the balanced texture of the captured surfaces. Agisoft Metashape 2.1.1 enabled photogrammetric reconstruction. In Table 1, the main outcomes are summarized.

Table 1. Photogrammetry outcomes for each Reconstruction Unit.

Reconstructive Unit (RU)	Subsets	Number of Registered Images	Number of Dense Cloud Points	High-Poly Mesh Polycount	GSD (mm/pxl)
RU 1—Horizontal band	R 1.1 Leather Hangings	8	8,250,310	16,500,620	0.253

	R 1.2 + R 1.2.1 Intrados − window shutter	57	6,091,920	12,183,840	0.473
	R 1.3 + R 1.3.1 Frame − Door	28	8,990,980	17,981,960	0.381
RU 2—Floor	Floor	570	134,224,416	268,448,832	0.251
RU 3—Ceiling	Ceiling	59	7,348,230	14,696,460	0.484

e. CG reconstruction: Surface property reconstruction and texturing are performed starting from photogrammetric data, using the Foundry Modo 17 for mesh optimization and parameterization and rendering, and Adobe Substance Sampler 3.4.1 for texture authoring, following a procedure established in a previous study [45]. The procedure to reconstruct architectural elements from parts belonging to other components of the building or other buildings was as follows: retopology of the frame, parametrization, texture application in the adopted photogrammetric software, semantic partition of the various travertine blocks that form the original frame, elimination of redundant parts, and finally reassembly of the parts (editing overlaps or gaps) (Figure 12).

To model the shape of the window frames—to be "carved" inside the leather walls—geometric and dimensional information obtained from the laser scanner survey of the gallery was used to reproduce, as a low-poly model, the ruled surface of intrados that concludes the window frame at the top. This approach was designed to simplify the creation of textures from various photographic samples of frescoes with similar themes (Figure 13). The floor, the third element in the semantics of the reconstruction, was recreated starting from the terracotta pavement of the *Galleria*, the room used as a planimetric reference for the *Quarto Camerino*. Since the intention was not to reproduce the *Galleria* floor exactly as it is, semantic partition was carried out to create a replica that was coherent but not identical. Semantics were used to identify seven types of different spatial organizations of the tiles. Seven high-detail orthophotos were used as the basis for creating a mosaic of color maps (albedo). From these, we obtained the albedo, normal, and roughness channels (Figures 14 and 15).

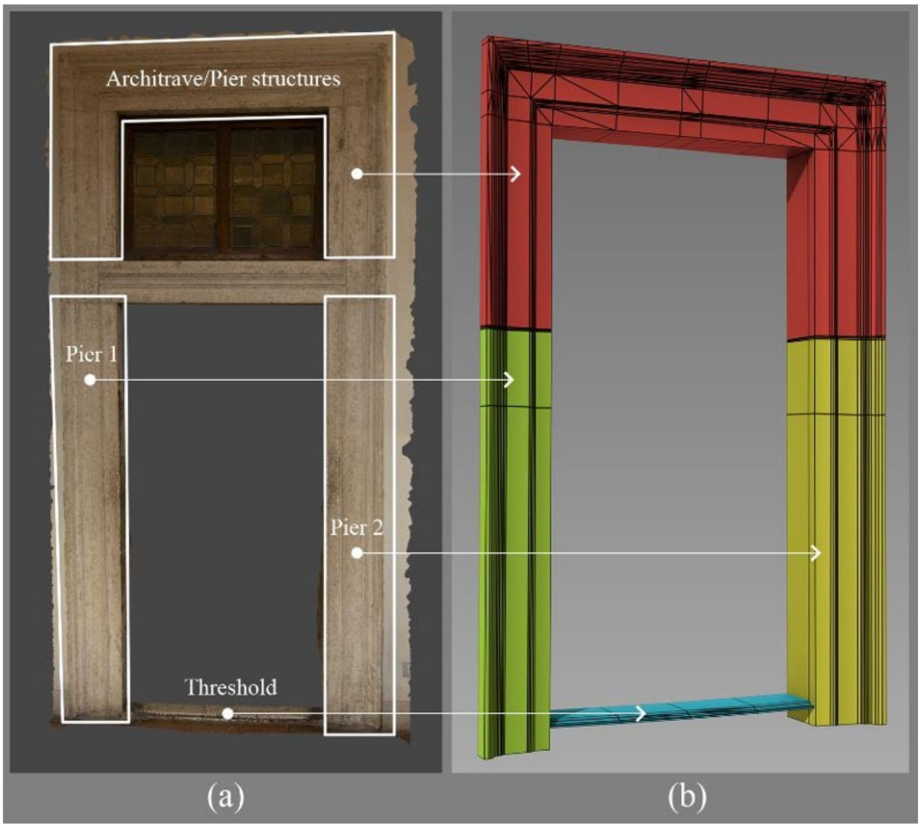

Figure 12. (**a**) A high-detail model from photogrammetry that will serve as the basis for creating (**b**) an optimized version of a door with a travertine frame in the *Quarto Camerino*.

Figure 13. (**a**) Three-dimensional model of the system consisting of the intrados and its corresponding window (from the *Galleria*), (**b**) reconstructive model of the intrados (*Quarto Camerino*), (**c**) texture of the reconstructive model with the numbering of the areas corresponding to groups of prevailing normals of the intrados.

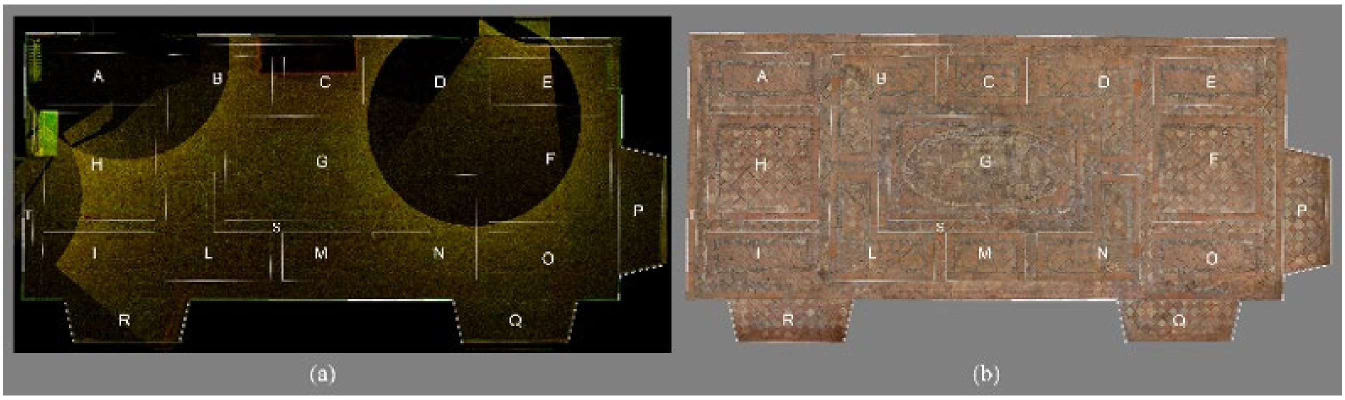

Figure 14. (**a**) orthophoto of the point cloud with segmentation corresponding to different types of spatial organization of the tiles. (**b**) final orthophoto with assembling of the various parts obtained by photogrammetry.

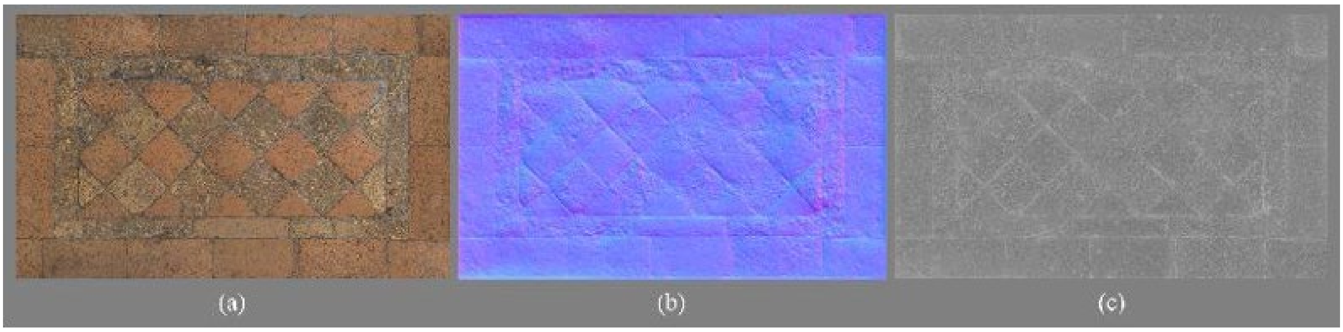

Figure 15. Sample of a terracotta flooring section: (**a**) albedo; (**b**) normal map; (**c**) roughness map.

The walls covered with *corami* (leather panels) featuring gold phytomorphic patterns on a green background were reconstructed using the procedural system based on VPL described in paragraph 4.2. The complex optical behavior of the surfaces included conductor/metal reflections and dielectrics. Beginning from a high-resolution orthophoto generated through the photogrammetry of similar wallpapers, we developed a set of textures able to accurately replicate gold leaf behavior by using the "metalness" channel and the painted leather using the dielectrics (Figure 16).

Figure 16. Set of textures aimed at simulating the optical behavior of leather sheets (metallic and dielectric) and their simulation using ambient lighting generated by an HDR image.

f. Analysis of perceptual optimization: The evaluation carried out using formula (4) was performed on three key frames of a potential exploration, D_{os}, D_{es}, D_{cu}, which involves a progressive approach to an artwork. The dimensions of the reconstructed space of the *camerino* are a = 4.34 m, b = 9.60 m, and c = 4.25 m. At this stage of the process, it is necessary to place artworks into the scene to verify perceptual criteria. We introduced the *Circoncisione di Gesù* by Ludovico Mazzolino (Gallerie degli Uffizi, Firenze), whose presence in the *camerino* is well documented by sources. Its measures are a′ = 0.441 m, b′ = 0.071 m, and c′ = 0.54 m. In compliance with the inequations in paragraph 4, three renders were calculated with the following characteristics: D_{os} = 6 m, D_{es} = 2 m, D_{cu} = 0.8 m (Figures 17–19). The corresponding values of E, which quantify the perceptual reliability of the virtual visit, are as follows: D_{os} = 72.22%, D_{es} = 57.09%, D_{cu} = 61.86%. The results of this analysis, considering numerical quantification of the reliability of the proposed process, are manifold. Firstly, the role of RU1, i.e., the horizontal band of the reconstructed space, emerges as a priority.

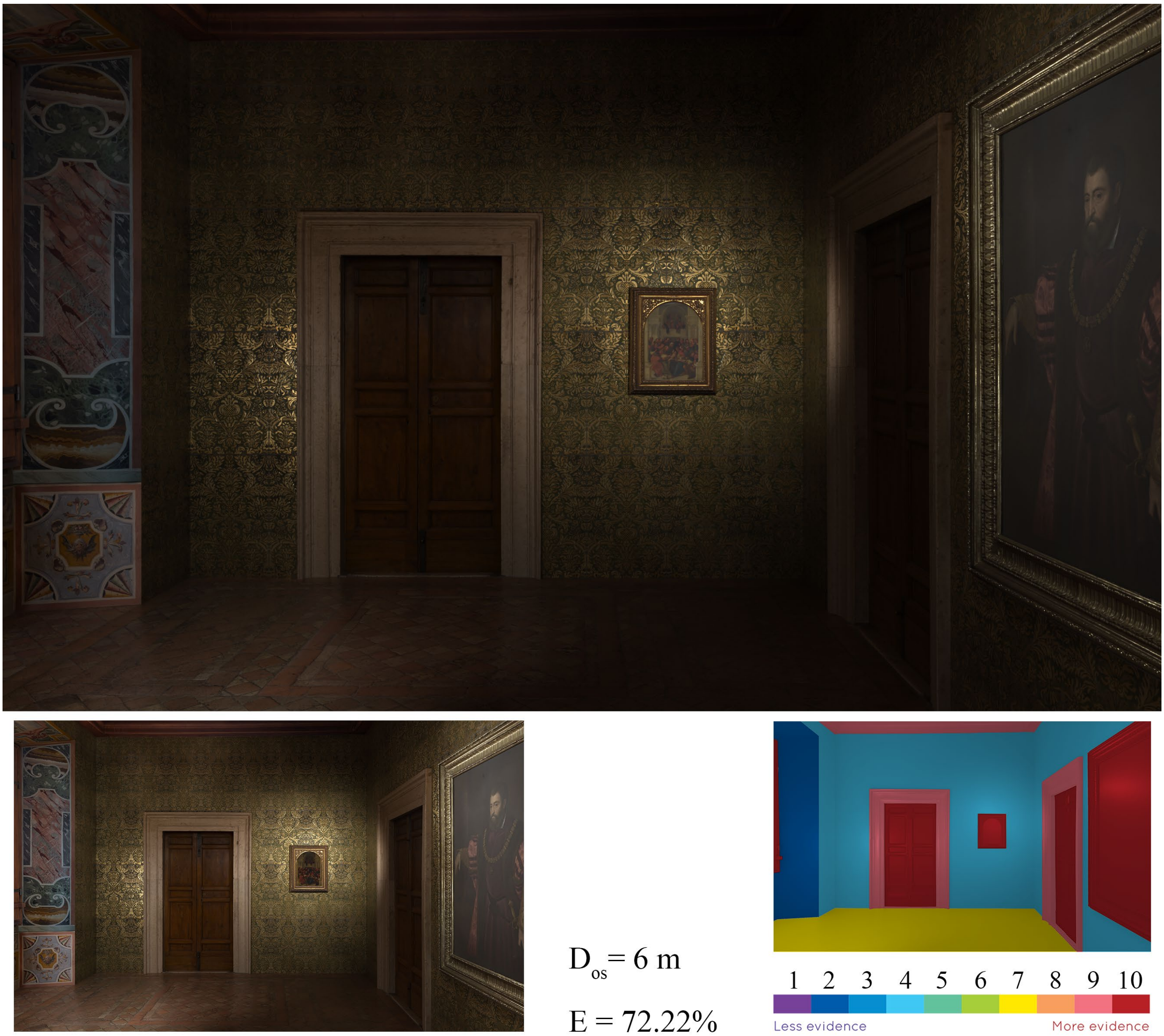

Figure 17. Simulation, overall scale distance.

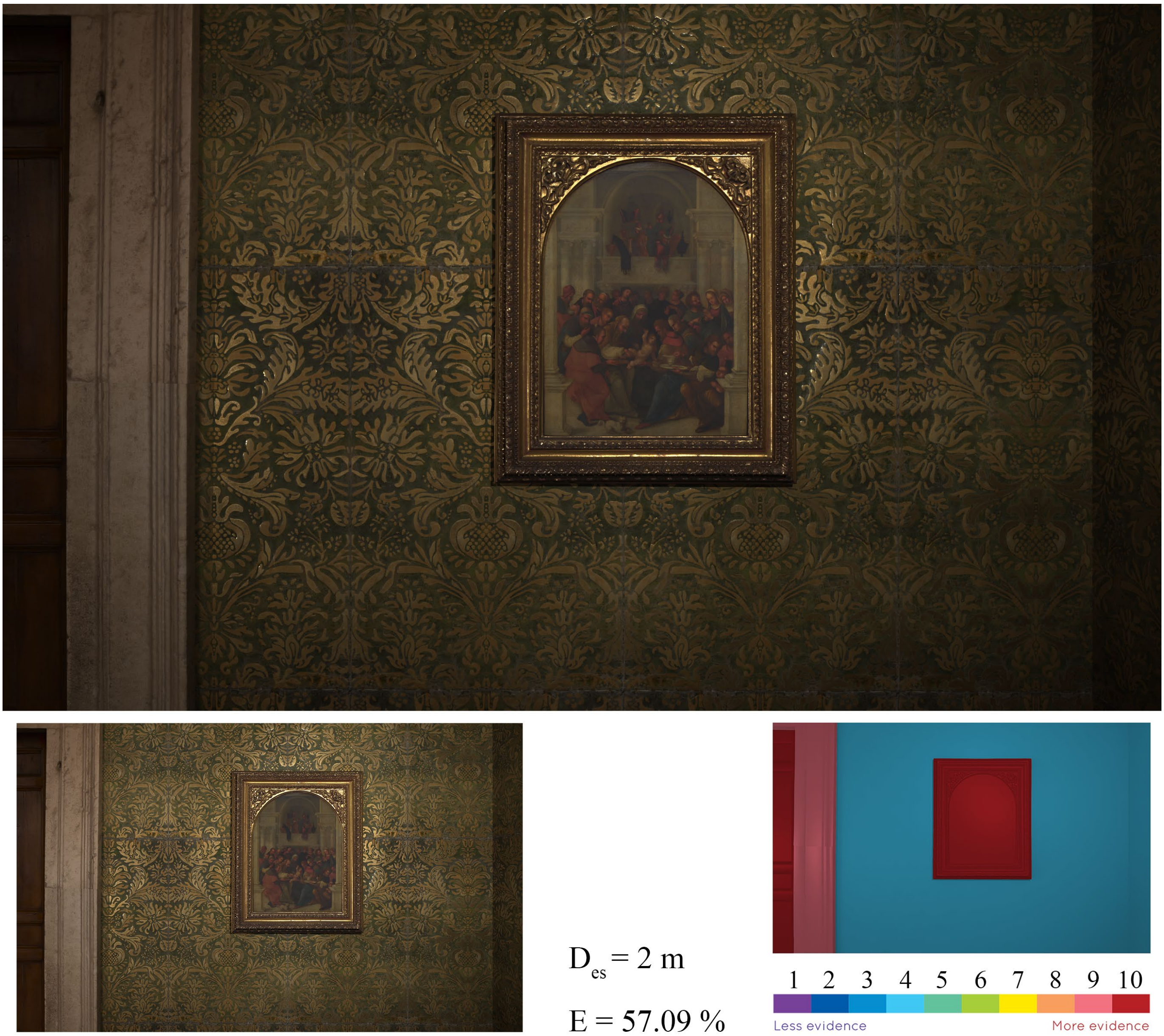

Figure 18. Simulation, exhibition setup distance.

In our case, we have high chromatic and material reliability, while the reproduced phytomorphic pattern is not based on iconographic or written sources of the original finishing. The perception of Des is less rich due to the limited number of paintings placed in the scene. However, we know from the description of the goods in the *Inventarium bonorum bonae memoriae Hippoliti Estensis Cardinalis de Ferrara*, 1572, that the number of artworks was much higher. In other words, the perceptual value at the time was much higher than the calculation value. Figures 17, 18, and 19 show the perceptual optimization results.

g. Lighting simulation: The virtual model shown in Figures 1 and 17–19 has been rendered with artificial lighting that has some basic characteristics of the lighting used to view paintings at the time. Specifically, the lighting used has the same color temperature and intensity as the flame-based light (measured values ranging from 1200° K to 1400° K for the two types of possible candles). This makes it possible to carry out a preliminary study using the digital scene, pending rendering with simulated lighting in all its components, which will be the final step of the "Dark Vision Experience" project. The temporary solution chosen here makes it possible to show all the basic perceptual components, such as the vibrancy of the gilded components (frames and covers characterized by pure gold inlays), *chiaroscuro*, the presence of extremely low lighting levels, soft shadows, and circumscribed areas where the lighting accentuates painted surfaces and reflections.

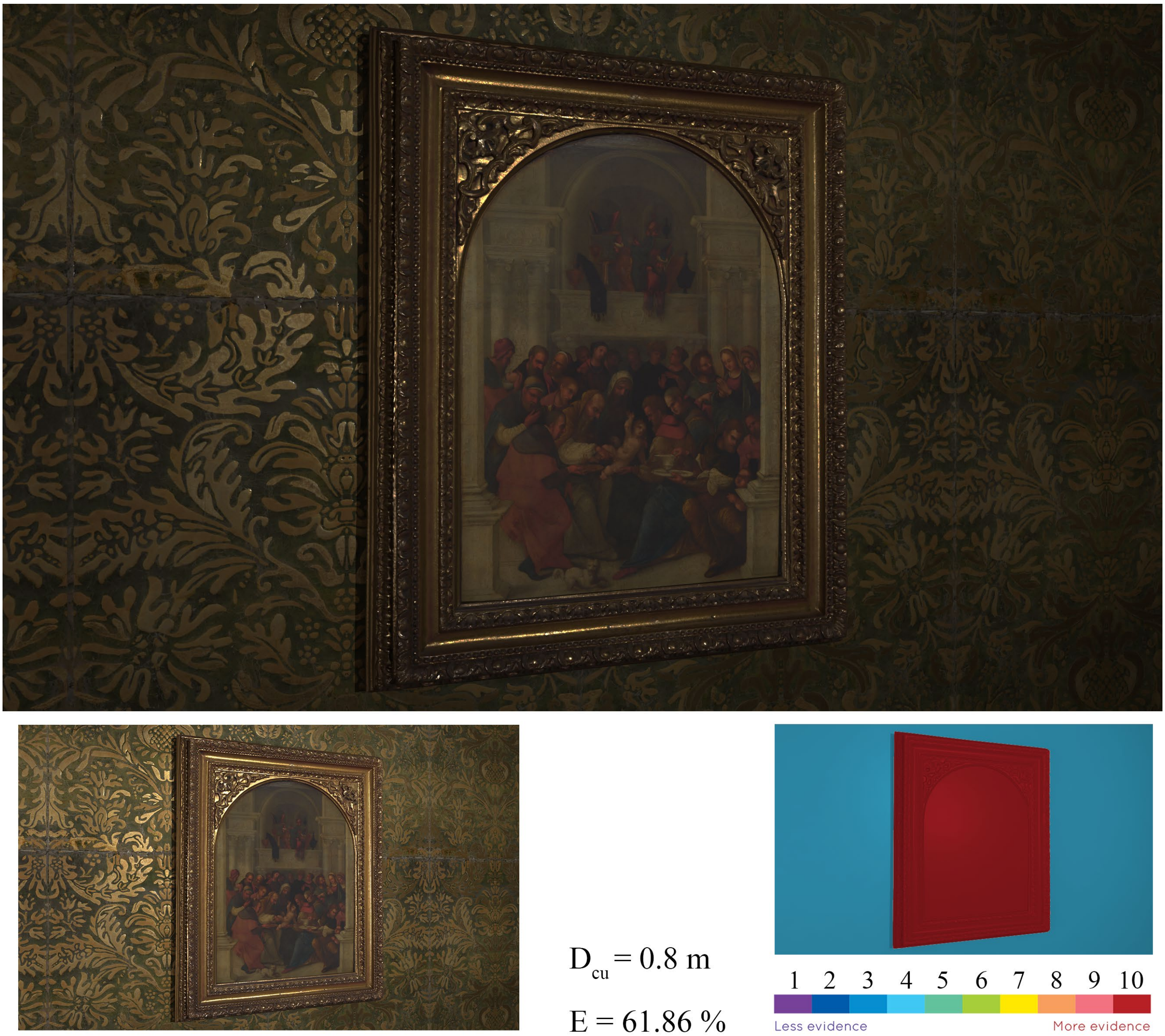

Figure 19. Simulation, close-up distance.

6. Conclusions

This paper addresses the topic of the methods and techniques for the digital reconstruction of the *camerini*, which are precursors to the modern museum. Because of their historical significance, they have been the subject of numerous art historical studies and, more recently, experiments using 3D modeling techniques with varying levels of detail and precision.

To overcome this level of experimentalism and move toward a more consistent methodology, this study proposes a specific and systematic solution to reconstruct and visualize the *camerini* environment, developed according to three different points of view: that of the art historian, that of the surveyor, and that of the designer.

The method was developed based on a well-known case study, the *camerino/studiolo* of Ippolito d’Este in Tivoli, and this article illustrated the general criteria and methods used, derived from the development of existing working protocols, adapted and enriched with innovative elements. Particular attention was paid to overcoming some critical aspects that emerged in the evaluation of previous studies, such as semantic modeling, explicit statements of reconstructive sources and their reliability for each part, survey methods, the replication of optical reflection properties of materials, study of the effect of light, and the addition of perceptual criteria motivated by the use of *camerini*. A process of *ex-ante* evaluation of model characteristics, rather than ex-post through the traditional modeling procedure, allowed for an express focus on problems and solutions.

Finally, the development of perceptual criteria made it possible to develop model-building techniques capable of philologically reproducing not only lost spaces but also their mood and the way they allowed the work of art to be observed.

Future work concerning the process of 3D digital reconstruction of the c*amerino* for art exhibition purposes will undergo further refinements to accurately simulate the lighting conditions of ancient oil lamps used to illuminate paintings and spaces during nocturnal visits. Additionally, the project will explore perceptual evaluations of the reconstructed environment based on varying inclinations of different user groups (art historians, interior design and exhibition experts, curators, visitors). This approach will aim to quantify the observation tendencies of these categories, enhancing the reliability of the visit experience in relation to the now-lost ancient reality, potentially aiding the design of multiple exhibition hypotheses.

Author Contributions: Conceptualization, C.O., L.C., and M.G.; methodology, C.O., M.G., F.F., and L.C.; resources, L.C., F.F., and O.C.P.; formal analysis, L.C. and F.F.; background studies, M.G. and C.O.; data curation, L.C. and F.F.; writing—original draft preparation, F.F., C.O., and O.C.P.; writing—review and editing, M.G.; visualization, F.F.; supervision, M.G. and C.O.; project administration, C.O., L.C., and M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research is founded by EU—Next Generation EU, Mission 4 Component 1 PNRR—PRIN_2022—P2022XB78F_001—CUP: E53D23018920001.

Data Availability Statement: NData are contained within the article.

Acknowledgments: The authors would like to thank the director of the Istituto Autonomo Villa Adriana e Villa d’Este Andrea Bruciati, and the staff of the institute, in particular Laura Baruzzi, and Davide Bertolini for their support and collaboration in the research that led to this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Occhipinti, C. I. «Locus adeo obscurus»: Camerini rinascimentali e fruizione notturna (introduzione al progetto PRIN PNRR 2022 «Dark Vision Experience»). *Horti Hesperidum. Studi di storia del collezionismo e della storiografia artistica* 2023, II. https://www.horti-hesperidum.com/hh/horti-hesperidum-2023-2-10/
2. Agosti, B. *Paolo Giovio. Uno Storico Lombardo Nella Cultura Artistica Del ’500*; Olschki: Firenze, Italy, 2008.
3. Barocchi, P.; Gaeta Bertelà, P. *Collezionismo Mediceo E Storia Artistica, I: Da Cosimo I a Cosimo II*; SPES: Firenze, Italy, 2002; pp. 15–16, 92 and passim.
4. Longhi, R. *Officina Ferrarese (1934)*; Sansoni: Firenze, Italy, 1975; p. 25.
5. Gundersheimer, W.L. (Ed.) *Art and Life at the Court of Ercole I d’Este: The «De Triumphis religionis» of Giovanni Sabadino Degli Arienti*, Libraire Droz: Ginevra, Switzerland, 1972; p. 72.
6. Occhipinti, C. *Giardino Delle Esperidi. Le tradizioni Del mito E La Storia Della Villa d’Este a Tivoli*; Carocci: Roma, Italy, 2009.

7. Mantovani, R.; Serafini, F. Lo studiolo virtuale di Urbino. In *Matematica E Cultura*; Hemmer, M., Ed.; Springer: Milano, Italy, 2008; pp. 127–137.
8. Zambruno, S.; Urcia, A.; De Vivo, M.; Vazzana, A.; Iannucci, A. From Sources to Narratives: The role of Computer Graphics in Communicating Cultural Heritage Information. *J. Mass Commun.* **2017**, *7*, 497–502.
9. Lo studiolo di Gubbio. Available online: https://framelab.unibo.it/lo-studiolo-di-gubbio/ (accessed on 15 December 2024).
10. Lo studiolo di Belfiore. Available online: https://framelab.unibo.it/lo-studiolo-di-belfiore/ (accessed on 15 December 2024).
11. Isabella Virtual Studiolo. Available online: https://ideastudiolo.hpc.cineca.it/ (accessed on 15 December 2024).
12. Apollonio, F.I. The Three-Dimensional Model as a 'Scientific Fact': The Scientific Methodology in Hypothetical Reconstruction. *Heritage* **2024**, *7*, 5413–5427.
13. Münster, S.; Apollonio, F.I.; Blümel, I.; Fallavollita, F.; Foschi, R.; Grellert, M.; Ioannides, M.; Jahn, P.H.; Kurdiovsky, R.; Kuroczynski, P.; et al. *Handbook of Digital 3D Reconstruction of Historical Architecture*; Springer Nature: Cham, Switzerland, 2024.
14. Kuroczyński, P.; Pfarr-Harfst, M.; Münster, S. (Eds.) *Der Modelle Tugend 2.0: Digitale 3D-Rekonstruktion Als Virtueller Raum Der Architekturhistorischen Forschung*; Heidelberg University Press: Heidelberg, Germany, 2019.
15. Pfarr-Harfst, M. Digital 2D and 3D visualizations as iconic epistemological models in Germany. *SCIRES-IT-SCIentific RESearch Inf. Technol.* **2020**, *10*, 19–30.
16. Micoli, L.L.; Malik, U.S.; Guidi, G. Virtual Reconstruction of no longer Existing Archaeological Structures in Highly Urbanized Areas. *Stud. Digit. Herit.* **2024**, *20248*, 1, 36–66.
17. Rodríguez-Moreno, C. Depicting the Uncertain in Virtual Reconstructions of Architectural Heritage. In *Graphic Horizons. EGA 2024*; Hermida González, L., Xavier, J.P., Pernas Alonso, I., Losada Pérez, C., Eds.; Springer Nature: Cham, Switzerland, 2024; pp. 120–127.
18. Apollonio, F.I.; Fallavollita, F.; Foschi, R. The Critical Digital Model and Two Case Studies: The Churches of Santa Margherita and Santo Spirito in Bologna. *Nexus Netw. J.* **2023**, *25*, 215–222.
19. Kensek, K.M.; Swartz Dodd, L.; Cipolla, N. Fantastic reconstructions or reconstructions of the fantastic? Tracking and presenting ambiguity, alternatives, and documentation in virtual worlds. *Autom. Constr.* **2004**, *13*, 175–186.
20. Zuk, T.; Carpendale, S.; Glanzman, W.D. Visualizing temporal uncertainty in 3D virtual reconstructions. In Proceedings of the 6th International Conference on Virtual Reality, Archaeology and Intelligent Cultural Heritage (VAST'05), Pisa, Italy, 8–11 November 2005; Eurographics Association: Goslar, Germany, 2005; p. 8.
21. Georgiou, R.; Hermon, S. A London Charter's Visualization: The Ancient Hellenistic-Roman Theatre in Paphos. In Proceedings of the 12th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage (VAST'11), Prato, Italy, 18–21 October 2011; Eurographics Association: Goslar, Germany, 2011; p. 8.
22. Perlinska, M. Palette of Possibilities: Developing Digital Tools for Displaying the Uncertainty in the Virtual Archaeological "Reconstruction" of the House, V 1,7 (Casa Del Torello Di Bronzo) in Pompeii. Master's Thesis, Lund University, Lund, Sweden, 2014.
23. Demetrescu, E.; Fanini, B. A white-box framework to oversee archaeological virtual reconstructions in space and time: Methods and tools. *J. Archaeol. Sci. Rep.* **2017**, *14*, 500–514.
24. Aparicio, P.; Figueiredo, C. El grado de evidencia histórico-arqueológica de las reconstrucciones virtuales: Hacia una escala de representación gráfica. *Rev. Otarq Otras Arqueol.* **2017**, *1*, 235–247.
25. Cáceres-Criado, I.; García-Molina, D.F.; Mesas-Carrascosa, F.J.; Triviño-Tarradas, P. Graphic representation of the degree of historical-archaeological evidence: The 3D reconstruction of the "Baker's House". *Herit. Sci.* **2022**, *10*, 1–14.
26. Siotto, E.; Cignoni, P. Digital methods and techniques for reconstructing and visualizing ancient 3D polychromy—An overview. *J. Cult. Herit.* **2024**, *68*, 59–85.
27. Hassan, A.T.; Fritsch, D. Integration of Laser Scanning and Photogrammetry in 3D/4D Cultural Heritage Preservation—A Review. *Int. J. Appl. Sci. Technol.* **2020**, *9*, 76–91.
28. Avena, M.; Patrucco, G.; Remondino, F.; Spanò, A. A scalable approach for automating scan-to-BIM processes in the Heritage field. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2024**, *48*, 25–31.
29. Alshawabkeh, Y.; Baik, A.; Miky, Y. Integration of Laser Scanner and Photogrammetry for Heritage BIM Enhancement. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 316.
30. Aicardi, I.; Chiabrando, F.; Lingua, A.M.; Noardo, F. Recent trends in cultural heritage 3D survey: The photogrammetric computer vision approach. *J. Cult. Herit.* **2018**, *32*, 257–266.
31. Jiang, C.; Lyakhov, D.; Rist, F.; Pottmann, H.; Wallner, J. Quad mesh mechanisms. *ACM Trans. Graph.* **2024**, *43*, 1–17.

32. Gonizzi Barsanti, S.; Marini, M.R.; Malatesta, S.G.; Rossi, A. Evaluation of Denoising and Voxelization Algorithms on 3D Point Clouds. *Remote Sens.* **2024**, *16*, 2632.
33. Bent, G.R.; Pfaff, D.; Brooks, M.; Radpour, R.; Delaney, J. A practical workflow for the 3D reconstruction of com-plex historic sites and their decorative interiors: Florence As It Was and the church of Orsanmichele. *Herit. Sci.* **2022**, *10*, 1–17.
34. Jesse, R.; Tomé, A. Finding the Lost 16th-Century Monastery of Madre de Deus: A Pedagogical Approach to Virtual Reconstruction Research. *Heritage* **2023**, *6*, 6213–6239.
35. Gabellone, F.; Ferrari, I.; Giuri, F.; Chiffi, M. 3D Technologies for a Critical Reading and Philological Presentation of Ancient Contexts. *Archeol. E Calc.* **2017**, *28*, 591–595.
36. Weill–Duflos, C.; Coeurjolly, D.; de Goes, F.; Lachaud, J.-O. Joint optimization of distortion and cut location for mesh parameterization using an Ambrosio-Tortorelli functional. *Comput. Aided Geom. Des.* **2023**, *105*, 12.
37. Boss, M.; Lensch, H.P.A. Single Image BRDF Parameter Estimation with a Conditional Adversarial Network. *arXiv* **2019**, arXiv:1910.05148.
38. Apollonio, F.I.; Fantini, F.; Garagnani, S.; Gaiani, M. A Photogrammetry-Based Workflow for the Accurate 3D Construction and Visualization of Museums Assets. *Remote Sens*. **2021**, *13*, 486.
39. Vaienti, B.; Apollonio, F.I.; Gaiani, M. Analysis of Leonardo da Vinci's Architecture through Parametric Modeling: A Method for the Digital Reconstruction of the Centrally Planned Churches Depicted in Ms. B. *Heritage* **2020**, *3*, 1124–1147.
40. Tatarchuk, N.; Dupuy, J.; Deliot, T.; Wright, D.; Narkowicz, K.; Kelly, P.; Netzel, A.; Costa, T. Advances in real-time rendering in games: Part I. In *ACM SIGGRAPH 2022 Courses (SIGGRAPH '22)*; ACM: New York, NY, USA, 2022; p. 1.
41. Sole, A.; Farup, I.; Nussbaum, P.; Tominaga, S. Bidirectional reflectance measurement and reflection model fitting of complex materials using an image-based measurement setup. *J. Imaging* **2018**, *4*, 136.
42. Georgiev, I.; Portsmouth, J.; Andersson, Z.; Herubel, A.; King, A.; Ogaki, S.; Servant, F. Autodesk Standard Surface: Reference Implementations. 2019. Available online: https://github.com/Autodesk/standard-surface/blob/master/reference/ (accessed on 14 December 2024).
43. Réby, K.; Guillem, A.; De Luca, L. Hybrid Construction of Knowledge Graph and Deep Learning Experiments for Notre-Dame De Paris' Data. In *Advances in Representation. Digital Innovations in Architecture, Engineering and Construction*; Giordano, A., Russo, M., Spallone, R., Eds.; Springer: Cham, Switzerland; 2024; pp. 467–482.
44. Besl, P.J.; McKay, N.D. A Method for Registration of 3-D Shapes. *IEEE Trans. Pattern Anal. Mach. Intell.* **1992**, *14*, 239–256.
45. Cipriani, L.; Fantini, F. Digitalization culture vs archaeological visualization: Integration of pipelines and open issues. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci*. **2017**, *42*, 195–202.