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

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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. The analysis of the *camerini*, true precursors of the modern museum, is not only a specific subject of study but also extremely relevant because it allows us to re-analyze 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 the possible problems in its 3D reconstruction, the article presents a method, and a workflow aimed at the reconstruction and visualization with high visual quality of these spaces and their features. Digital surveying technologies are integrated with advanced methods that allow the reproduction of the full optical properties of spatial surfaces and with tools for semantic modelling and visualization to generate a digital artefact 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

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1. Introduction

Art historians and collections historians until now have not focused on the capital importance of the Greek word *museion*. Originally referring, according to Strabo's well-known statement, to the places of cult 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 Erasmus's place of study, which he defined in Greek as *museion* and connected, not surprisingly, to the library (*adiunctus est bibliothecae*), had the characteristic 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 him to imagine the immense and lost magnificence of ancient Greece and the Rome of the Caesars through not only the reading of literary texts but also the vision of those precious artifacts that, lovingly guarded, precisely, in the shady of the *museum*, were revealed in the light of a dim and gushing flame to make *elegant* that *cramped* and *dark* place. Just a little later, in 1532, the word *museion* was attested in the correspondence of Benedetto, Paolo Giovio's brother, in reference to the palace, then under construction on Lake Como, where what later everyone would 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 in our own day, the Uffizi Gallery; thus, it was that 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 varying 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 memory, 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, 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 fifteenth and sixteenth centuries, contained riches and artistic heritages 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.

This paper aims to address this subject: the reconstruction of the spatial and visual characteristics of the *camerini*, true precursors of the modern museum. 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 varying levels of detail and precision. These projects have 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. In this sense, 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. The manuscript also discusses the issue of virtual restitution of the architectural structure with a view to 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 a proper appreciation of the material and stylistic qualities of the paintings belonging to different pictorial schools.

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To define the procedure, three different points of view are combined in a common methodological approach: that of the art historian (expert in the history of the design, construction, and evolution of buildings), that of the surveyor (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 the article, after a description of the state-of-the art in the *camerini* reconstruction, aimed to show the main point related to the specific space, for these issues a developed method was illustrated, focusing both the elaboration 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 problems addressed and solutions found, along with their evaluation (Figure 1).

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

2. State of the art

2.1. State of the art in the camerini reconstruction

The state of the art in the *camerini* 3D reconstruction 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 the visitor 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,* reproducing even 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, the 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 has allowed 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 meters, the shorter ones 2.8 and 2 meters; the ceiling, with a coffered roof was placed at a height of about 4 meters. 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 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: a first phase of high-resolution photographic acquisition of the original inlays, carried out directly at the Metropolitan Museum, which produced chromatically correct images; a 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 the exploration of the *studiolo* according to gamification logic, allowing the user to move in the virtual space with first person view and to observe every detail from different angles.

Despite the wealth of information, the lighting reproduction 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 a 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

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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 x 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 the Delizia over the centuries, including fires and military attacks, the paintings have been preserved and are now distributed among several museums in Europe.

The Belfiore *studiolo* was the subject of a valorization project launched in 2019 by the collaboration between FrameLAB of the University of Bologna, the Pinacoteca Nazionale di Ferrara and the Gallerie Estensi, focusing on digital storytelling and privileging the 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 that of other panels made by the same craftsman: Arduino da Baiso.

The wooden essences replicated in the 3D models were photorealistically 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, archaeological finds, and naturalistic curiosities-an impressive collection that was the pride of the Gonzaga family until it was dispersed in the seventeenth century. As lover of music and 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.

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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 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 get closer 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 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, explicit stating of reconstructive sources and their reliability for each part, methods of surveying, replication of optical reflection properties of materials, and the study of the effect of light must be carefully considered.

2.2. State of the Art in the Architecture Historical Reconstruction

In the last years an extensive 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 the interiors space and then also to the *camerini* [12, 13, 14, 15, 16].

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

- historical reconstruction source reliability
- geometric and photometric.

a. *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 of disappeared have been the subject of extensive literature [17]. The aim is to broadly distinguish between the function of the 3D model of 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

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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 Historical/Archaeological Evidence scale [22]. Several scholars have theorized about the use of a semantic structure in digital modelling 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 archaeologists 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 absence of documentary units. 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 archaeological 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 (RU) and a scale of historical-archaeological evidence. The RU refers to discrete components of a building that can be reconstructed individually based on available evidence, namely a sort of reconstruction semantics. The scale of historical-archaeological 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 archaeological data and historical understanding.

This method has been successfully employed in high-value archaeological research [25], demonstrating its effectiveness in ensuring accurate and well-documented reconstructions.

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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 RU and the evidence scale, this approach can provide concepts and tools for a robust framework for 3D reconstruction, ensuring that hypothesis acknowledged are not only visually accurate but also scientifically credible and transparent. As a matter of fact, RU 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 the RU and the scale of historical-archaeological 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 archaeological studies.

b. 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 led 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 RU is their origin. In this context, the reconstructions are primarily grounded in reality-based data, ensuring a robust and accurate foundation for further modelling 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, 28, 29, 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 modelling operations, or retopology) [31, 32].

These techniques are recommended at the final stage of geometric reconstruction from reality-based data. This step, though not always mentioned in scientific literature, allows for better management of geometries and the optical reflectance of materials inferred in the geometric model. Optimized parametrization provides high control in geometric and mapping models, 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.

A second 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, 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 CGI [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 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 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 physically accurate visualization technologies.

3. Case study

Ippolito d'Este's *Quarto Camerino*, located on the top floor of the Este Palace in Tivoli, was 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 re-functionalization that changed its original purpose. The walls were covered with fine *corami* and decorated with works of immense value attributed to master such as Titian, Raphael, Jacopo Palma, and François Clouet. These paintings, now 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 reconstructive operation of *camerini* for research purposes will be explained. These derive from the development of existing work protocols, which have been customized and enriched with innovative elements to obtain digital representations of Renaissance *camerini.* Furthermore, these general criteria as developed 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: text sources only, uncertain location, current state in which original surfaces (floors, walls, ceilings) are unrecognizable, lack of information on the specific location of each artwork (Figure 2).

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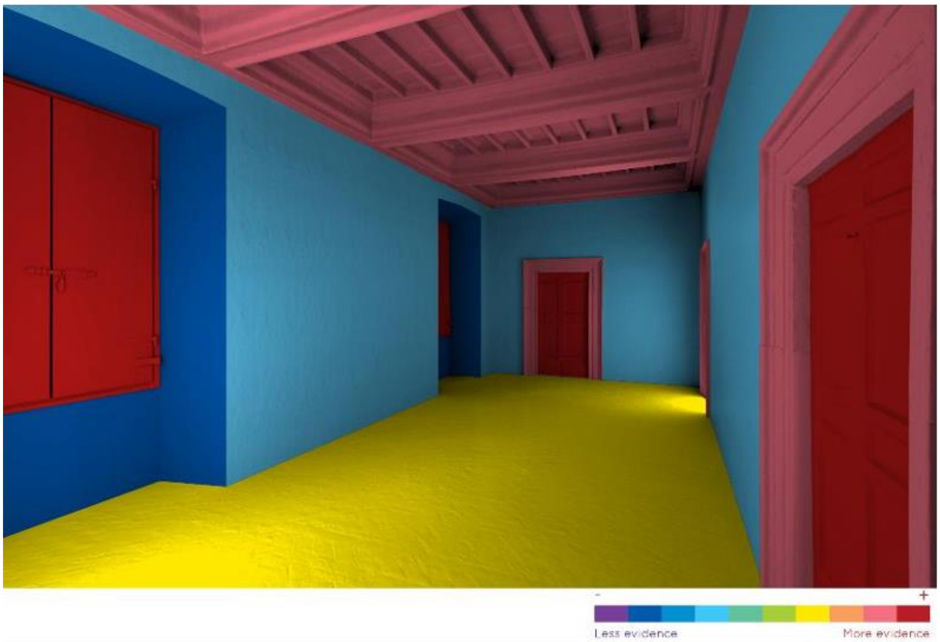

Figure 5. View of the reconstructive model with a scale depicting historical evidence. Colors applied to each RU correspond with different amount of evidence.

Finally, the traditional procedure of ex-post evaluation of the obtained result (validation) was not followed, but an ex-ante procedure was preferred, in which each choice was made a priori according to a path with several joint working groups among the different types of professional figures involved, in which the choices to be made were agreed from time to time. This procedure resulted in better overall efficiency, shorter time and more accurate results.

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 conceptual and technical workflows allowing the hypothetical reconstruction.

The following are the basic and characterizing steps.

The first concept in the reconstruction of a no longer existing or otherwise altered interior is to evaluate its position and consistency within the building that housed it. Indeed, the change in configuration of an interior space, attributable to functional causes, is much higher compared to that of the 'masonry box' that houses it. Hence, the need to elaborate both written sources and the available iconographic apparatus, as well as the current graphic documentation, to understand the position and volume most consistent with the available data. If a strategy based entirely on the use of material derived from the study of examples consistent with the sources is chosen (conjecture based on similar structures) (Figure 3), the information available for reconstruction must be homogenized and grouped into a series of reconstruction units (RU). Within these units we will observe the state of a variety of historical evidence. Typological, distributive, constructive, and functional affinities guide the criteria for positioning and arranging a reality-based RU within an obliterated space.

The resulting reconstruction, as part of a wider scene (such as a sequence of halls and rooms), requires a validation that is dynamic and extends beyond the conceptual limits of a single 'narrow view' of an RU ensemble. It is then important to introduce perceptual criteria to assess the reliability of a reconstruction not only from a privileged, external point of view but also in relation to the viewer's proximity to the artworks and the arrangement designed to house them, thereby enhancing their communicative, symbolic, and artistic impact.

The dimensions of the space to be reconstructed (its three-dimensional consistency) also depend on its placement within the building's elevation. The floor reserved for public and representative functions is generally much higher than those reserved for study and contemplative functions. Essentially, the necessary focus for a more attentive perception of artworks did not align with the 'expansion' of the plan and elevation. Conversely, the *camerini* were generally smaller spaces, but

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only in terms of size. The contained height was therefore intentional, and the location of a space with such a function should be sought on a floor of the building characterized by a limited ceiling height.

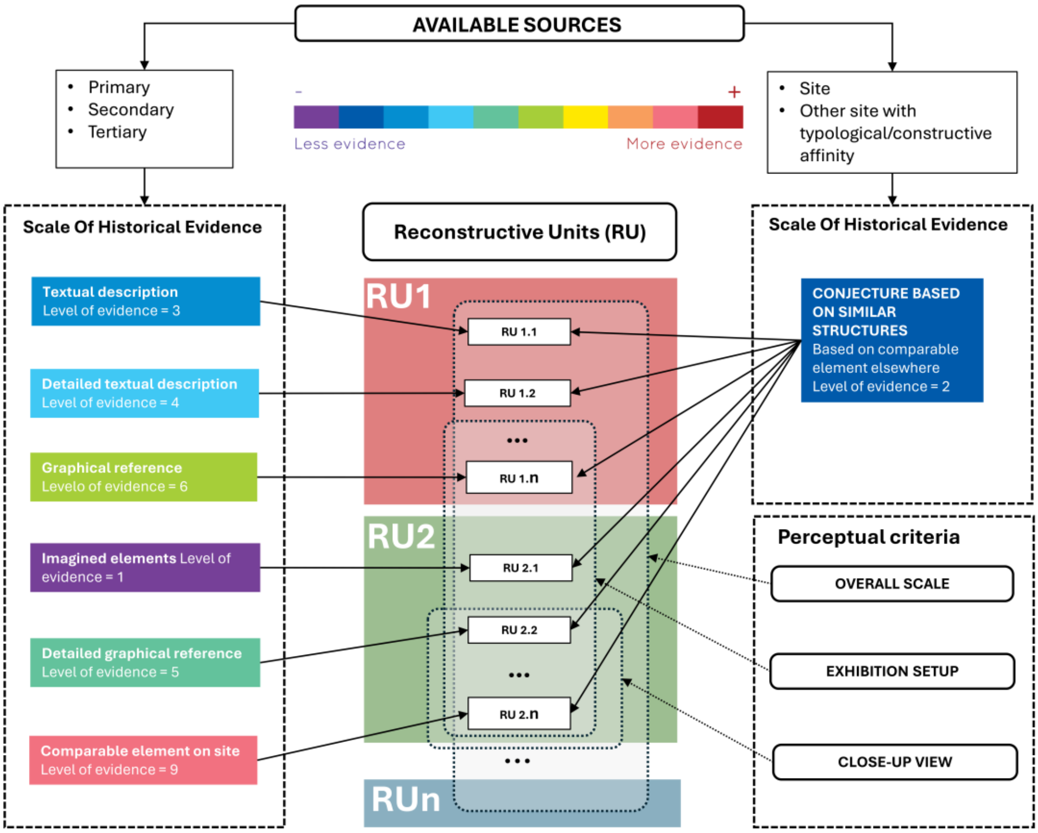

Figure 3. General diagram of the developed workflow in which the integration between sources and reality-based models to generate the individual reconstructive units is shown. Added to this process of transparency is a perceptual criterion of proximity to the reconstructive units.

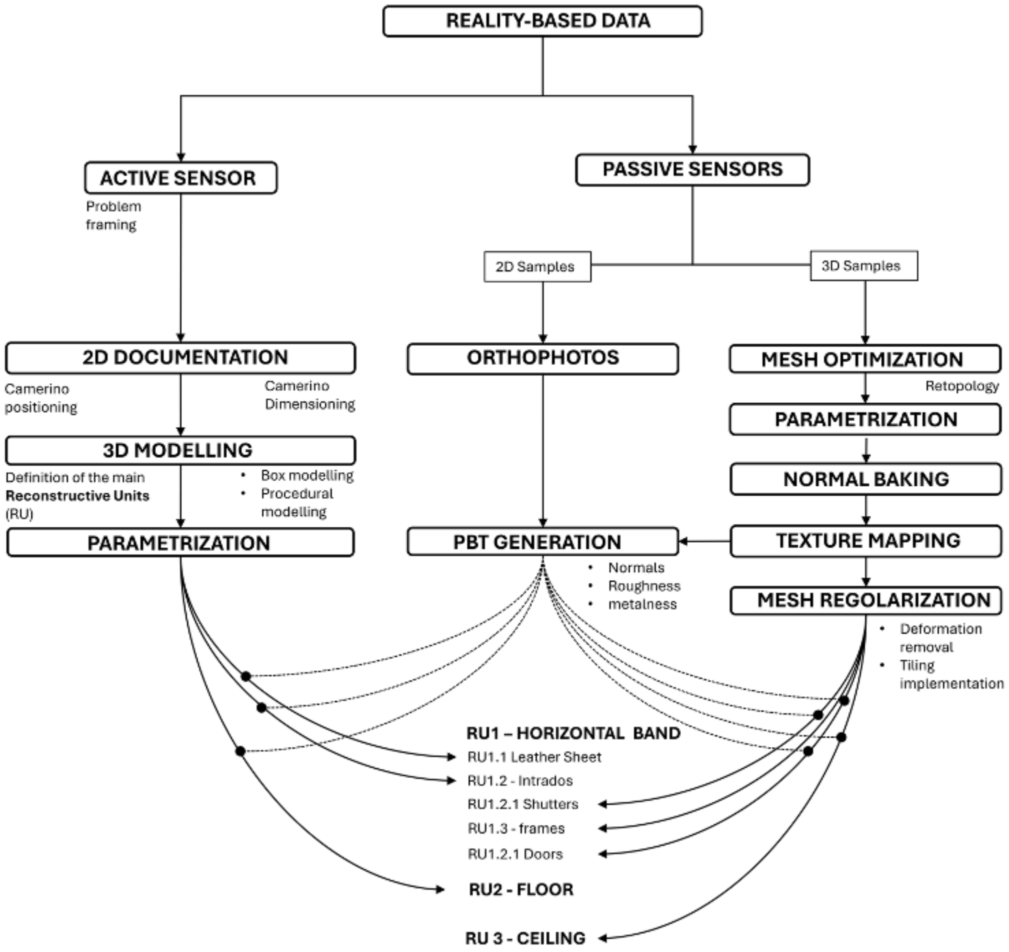

Figure 4. Diagram summarizing the production process of individual reconstructive units in terms of CG techniques employed. Crucial to the center of the process is the role of physically based texturing (PBT).

Once its position and consistency are determined, the 'masonry box' of the room must be articulated to achieve a perceptually coherent reconstruction with the available sources. The work structure we have developed is based on a semantic subdivision of the internal environment, which will facilitate the integration of digital models from heterogeneous sources (direct modeling, passive and active sensors). From a perceptual and semantic perspective, the digital reconstruction of an interior comprises three main parts, each playing a specific role. 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 designer 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). However, generally, if there are no natural light portals pierced on the intrados, domes, or vaulted systems with complex lacunars, the role of the intrados is subordinate to the "horizontal band" that serves as the backdrop for the artworks.

Once the semantics of the internal space are defined, at least in their essential lines, it is necessary to consider three aspects when deepening and detailing the reconstruction.

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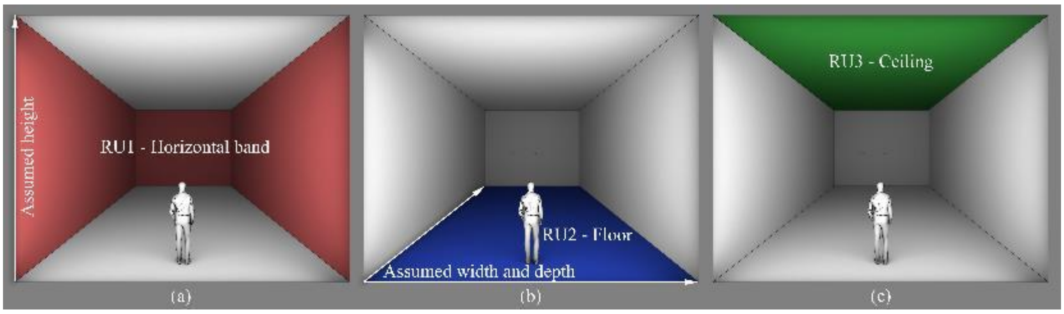

Figure 5. Macro Reconstructive Units (MRU) or macro semantics of the cabinet in relation to the exhibition function.

The first property is related to the topological regularity of each RU, whether they come from sensors or direct modeling. Models to be experienced need to be regularly shaped and, if possible, at minimum resolution, to ensure faithful reproduction of details, optical reflection properties of the surfaces and replica of their BRDF (Bidirectional Reflectance Distribution Function) behaviors [37], light transport between the object in the scene and easy management to insert variants, new features, information enrichment, communication through the internet. Therefore, the model should be low-poly and free of topological and geometric errors [38].

Specifically, because today CG replica of object properties is based on multitexture techniques [39] it is necessary to provide an adequate number of pixels in relation to the parametrized area to maintain a constant parameter called texel density across the entire system of assets introduced in the reconstruction. Topological regularity and the resulting facilitated texturing also allow for the creation of more effective and specific representations of the validity of the reconstructive hypothesis through false colors, to which different levels of coherence can be associated.

Reconstructive hypotheses methods and CG techniques were supported by interdisciplinary dialogue among various experts aimed at achieving a relationship between works of art and "exhibition" that is thematically coherent with the original [12]: in other words, the works are fixed and indisputable points of the reconstruction, the exhibition (relationship with illumination and background) will have a lower degree of reliability but will still be consistent with what we learned from written sources and typological comparison, and the environment (the building) as a whole will have geometric fidelity to the original, essentially determined by dimensional coherence with the still existing spaces and thus in overall relation to them.

Based on these premises and considering that the objective of the 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, an 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 (sub-millimetric details).

Let's now define, through a general quantification, what is meant by the scale of perception in the case of the reconstruction of environments like that of the 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 (Dos) 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 6a):

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

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

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The Exhibition Setup Distance (Des) 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 6b):

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

The close-up distance (Dcu) 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 6c). Therefore, denoting the dimensions of the artwork's bounding box as a'', b'', and c'', we have:

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

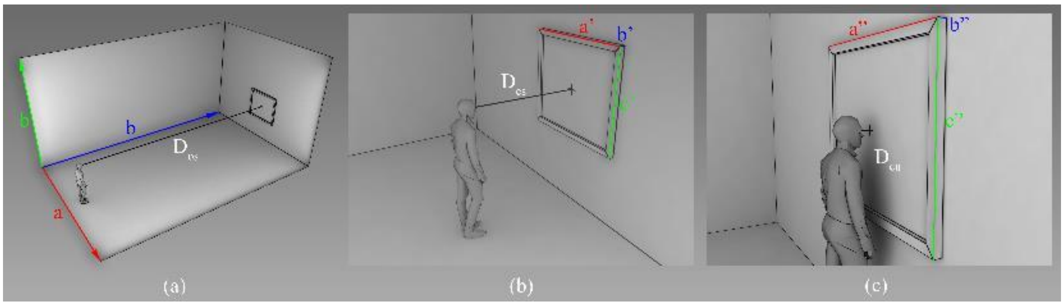

Figure 6. Viewing distances of the reconstruction.

Our 3D reconstruction of the 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). This method allowed us to achieve a high level of visual accuracy and detail by integrating both broad and fine-grained data. The results (Figure 1) demonstrate the effectiveness of combining different models to enhance the visual reliability of digital reconstructions with a specific focus on the integration of optimized 3D models constructed based on the criteria of maximum integrability and geometric flexibility, so they could adapt to different dimensions. On the topic of optimization and reliability of high-detail digital models for visualization we opted for render-to-texture solutions (baking) as well as, physically based texturing (PBT) to enhance realism and performance inside game engine and render engines, as well as to apparently increase the detail of low-poly models. The BRDF model employed will be of the "principled" type [40], which allows for accurate simulation of various material properties. The principled BRDF model, as detailed in several studies, 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, such as the Disney and Standard Surface models [41]. The price to pay for achieving such results is the need to use vertical work protocols, which are not always shared among various operators, both in terms of surveying and the model creation process. The integration of models from different sources also requires specialized skills in handling radiometrically correct textures to avoid annoying chromatic dominances that would undermine the realism of the simulation.

5. Results

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

a. Finding of the *Quarto Camerino* within Villa d'Este starting from the description of the goods in the I *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.

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344r-387r. [42] through a joint visit to the site by all the professionals involved (in addition to the authors, the officials of Villa Adriana and Villa d'Este)

b. check of the current consistency of spaces, find all spatial documentation related to them, measure them, and analyze transformations over time.

c. reconstruction of the current state based on the elements still present, and reconstruction of the missing elements based on their degree of reliability

d. geometric reconstruction

e. CG reconstruction of surface properties

f. perceptual analysis optimization

g. lighting simulation.

We will focus on the most relevant steps and technical solution adopted.

The reconstructive operation of the *camerino* is therefore the product of a meticulous process of gathering information and translating it into a series of RU hierarchically and coherently structured according to the sources.

The lack of iconographic sources required the search within Villa d'Este for a series of samples 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 7).

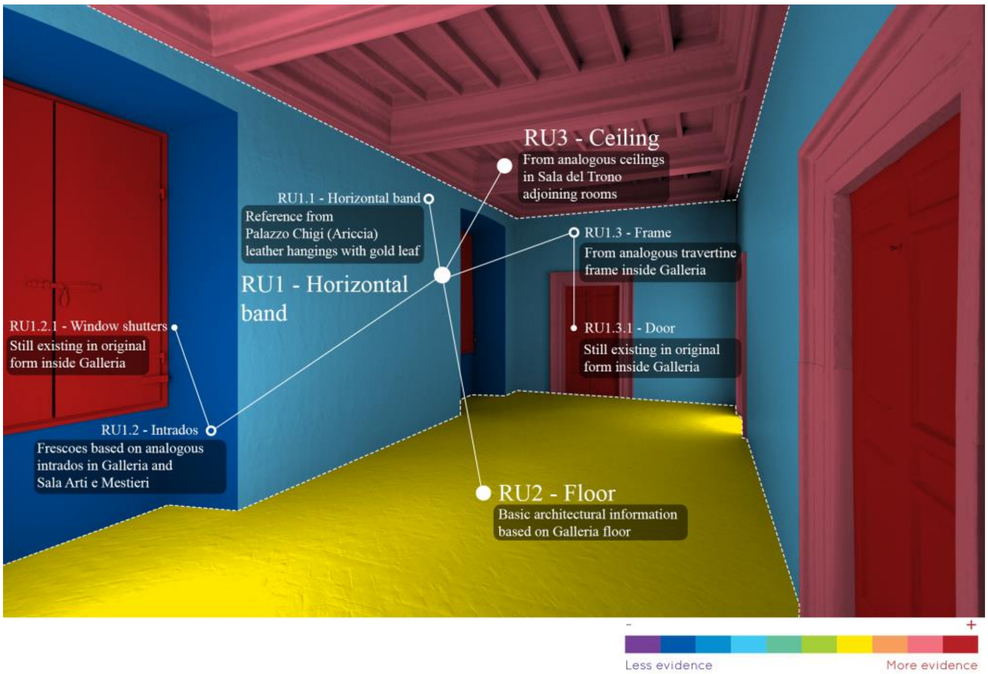

Figure 7. The model of the *Quarto Camerino* with the scale depicting historical evidence and, as label, the sources used for the reconstruction.

From a technical point of view 3D reconstruction of the 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.).

The CG process began with an on-site survey at Villa d'Este, where a series of rooms placed on the floor below the *camerino* (the second floor of the Villa) and important reference for its reconstruction were digitized using terrestrial laser scanning technology (Figure 8). This acquisition allowed us to obtain the planimetric and altimetric dimensions of the area of Villa d'Este 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 best reference for the room that accommodated the *Quarto Camerino*. Many elements that are no longer recognizable in the rooms that

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housed the *camerino* were probably very similar, such as the window casings, the door frames, the doors themselves, and the floors.

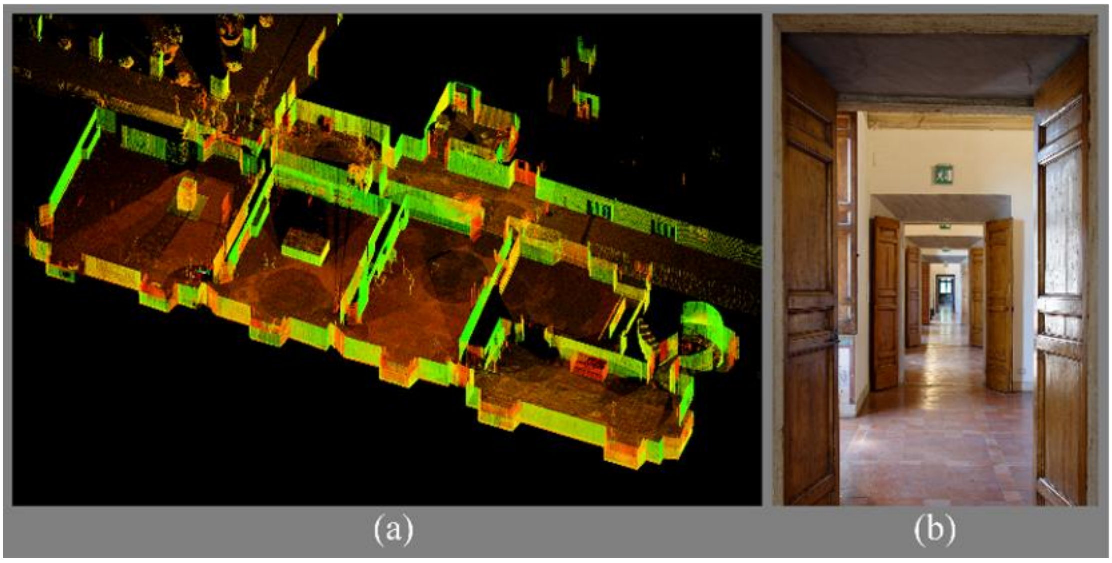

Figure 8. (a) Laser scanner survey of the northwest wing of the palace. (b) sequence of rooms, functionally connected by a series of doors aligned along the main façade.

The 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 9). However, this space should be located on the upper floor, characterized by a lower ceiling height compared to that of the below gallery. Based on these considerations, a plan view and a schematic elevation have been developed to be used for the subsequent interpretative steps necessary to 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 remain rooms of the same floor in Villa d'Este. Similarly, it was necessary to create a series of models (RU) 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).

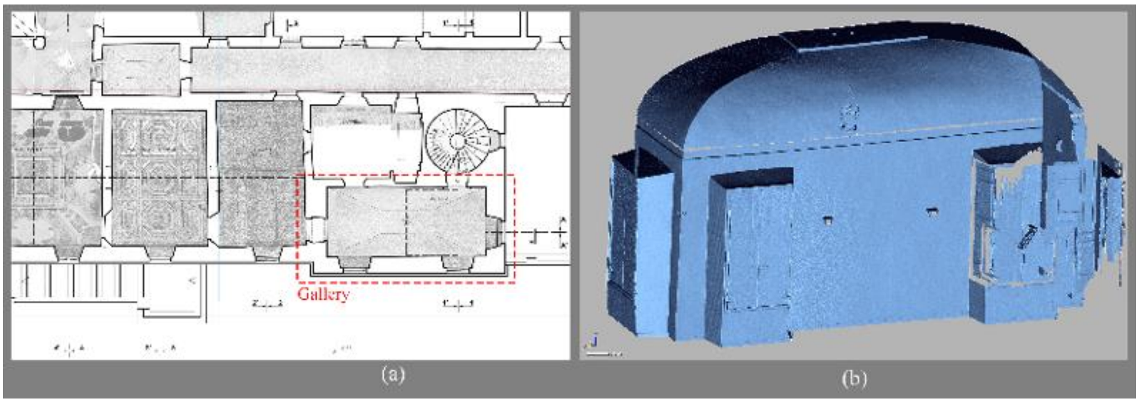

Figure 9. The *Galleria*: a probable reference for creating a reconstructive plan.

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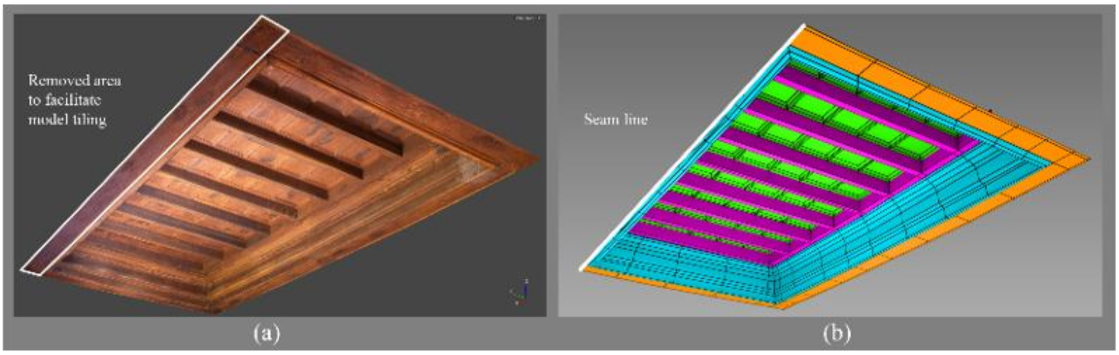

Figure 10. Photogrammetric model of a wooden ceiling consistent with that of the *Quarto Camerino*.

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.

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. Consequently, it will be necessary to prepare a series of architectural elements, acquired at high resolution through photogrammetry and then optimized [44].

These elements should be interactively adaptable to a range of dimensional modifications to ensure compatibility with the hypotheses evaluated by the interdisciplinary team. This latter aspect mainly concerns the wooden ceiling and the door frames. An analogous workflow was chosen for the travertine frames, which feature recurring moldings and a characteristic window above the actual door to allow light to penetrate even into the innermost rooms of the palace, far from the windows. In this case, there was no need to create frames to be juxtaposed in sequence but rather individual elements to be adapted to the openings.

The procedure used was as follows: retopology of the frame, parametrization, texture application in the employed 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 11). The walls are covered with corami (leather panels) featuring gold phytomorphic patterns on a green background. From a modeling perspective, 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) [45] was chosen, which creates arrays where the basic element is the single piece of wallpaper (Figure 12). The individual walls are automatically filled with rectangular leather 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.

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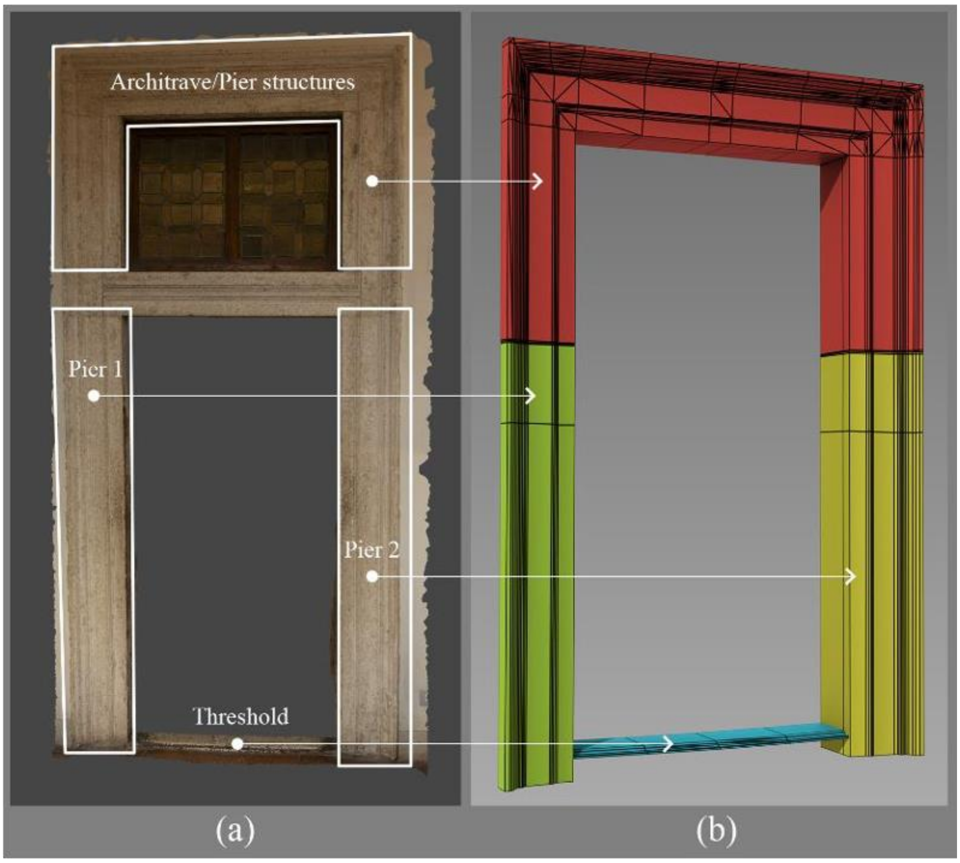

Figure 11. (a) a high-detail model from photogrammetry that will serve as the basis for creating (b) an optimized version of door with a travertine frame to the *Quarto Camerino*.

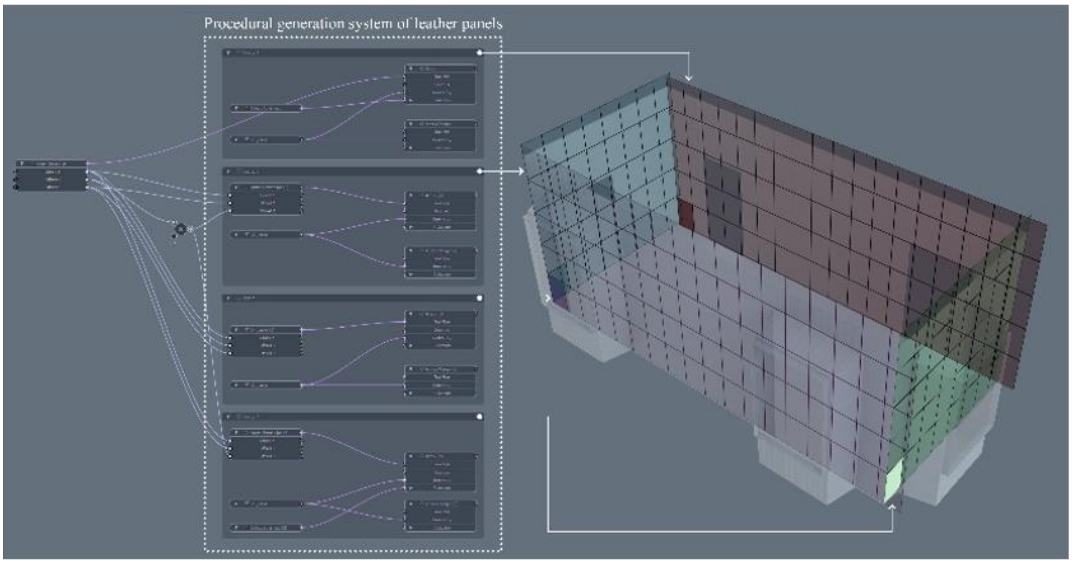

Figure 12. Procedural system based on Visual Programming Language (VPL).

For the modeling of 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 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).

Figure 13. (a) 3D 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.

For the flooring, the third element in the semantics of the reconstruction, it was not necessary to carry out a detailed photogrammetric survey that extensively documented the entire flooring of a room. The reason is that, like much of the flooring on the second floor of Villa d'Este, the original terracotta tiling has been lost or heavily replaced. However, in the room known as *Galleria*, used as a planimetric reference for the *Quarto Camerino*, we still have an original terracotta floor *in situ*, although in some areas the presence of modern tiles is clearly noticeable. Since the intention was not to reproduce the *Galleria* floor exactly as it is, a semantic partition was carried out to create a replica that is coherent but not identical. Semantics were used to identify seven different types of different spatial organization of the tiles. For each type, a detailed photogrammetric survey was conducted, and the results—seven high-detail orthophotos—were used as the basis for creating a mosaic of color maps (albedo).

From these, using a physically based texture authoring application we obtained the albedo, normal, and roughness channels (Figures 14, 15).

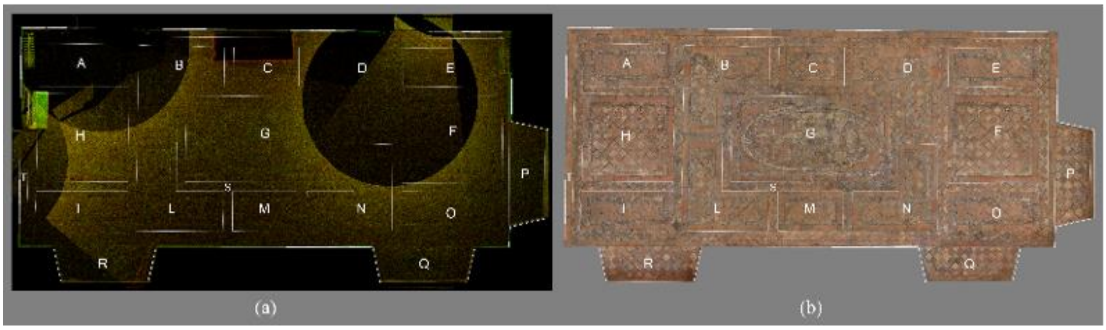

Figure 14. Different types of different spatial organization of the tiles.

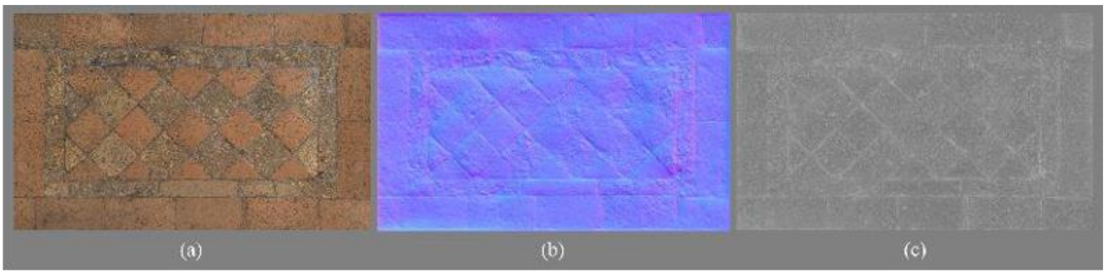

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Figure 15. Sample of a terracotta flooring section: (a) albedo; (b) normal map; (c) roughness map.

For the corami we achieved a realistic representation of a complex optical behavior of surfaces including conductor/metal reflections and dielectric [46]. Beginning from a high-resolution orthophoto generated through photogrammetry of similar wallpapers, we developed a set of textures. Specifically, we aim to replicate the representation of gold leaf applied to phytomorphic decorative motifs by using the "metalness" channel, and dielectrics for painted leather (Figure 16).

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

6. Conclusions

This paper deals with the issue of digital reconstruction of the *camerini*, precursors of the modern museum, and for this reason the subject of numerous studies in art history, and recently reconstructed as 3D digital models, made with different levels of detail and precision. The study proposes a specific and systematic method of reconstruction and visualization with high visual quality, developed according to three different points of view: that of the art historian, that of the surveyor and that of the designer.

The method has been developed based on a well-known case study, the *camerino/studiolo* of Ippolito d'Este in Tivoli, and the article illustrates the general criteria and methods used, derived from the development of existing working protocols, adapted and enriched with innovative elements. Particular attention has been 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, 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 a rapid focus on problems and solutions.

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

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Figure 17. Simulation, overall scale distance.

Figure 18. Simulation, exhibition setup distance.

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