Frontiers of the Past in the Digital World: Multidisciplinary Collaboration in the 3D Reconstitution of Medieval Border Towns

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Figure 1: Panoramic view of the 3D reconstitution of Castelo de Vide in the 16th century.

Abstract

The virtual reconstitution of Castelo de Vide, Portugal, within the FRONTOWNS project, highlights the challenges and successes of multidisciplinary collaboration in heritage preservation through 3D modeling. The goal was to reconstruct the town's urban evolution, focusing on its role as a border settlement from the 13th to 16th centuries. The project combined archaeological evidence, historical sources, and digital technologies like photogrammetry and 3D scanning. Co-creation workshops aligned diverse knowledge, leading to creative solutions that balanced historical accuracy and technical feasibility. Despite budget constraints, it produced a high-quality digital reconstitution with insights for future virtual heritage projects.

Keywords: Virtual heritage, Digital modeling, 3D reconstitution, Middle Ages.

Index terms: •Applied computing~Arts and humanities• Human-centered computing~Collaborative and social computing~Collaborative and social computing theory, concepts and paradigms~Collaborative content creation• Human-centered computing~Visualization

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1 Introduction

In the last three decades, the study of urban centers, buildings, and historical artifacts adopted multidisciplinary approaches, driven by advances in digital technologies. This has led to conceptual and methodological reflections—such as the differences between restoration and virtual reconstruction, or between reconstruction and simulation/model [1]—and to new practices for the analysis, and reconstitution of spaces, and communication of results. Examples of digital reconstitutions include medieval cities such as Constantinople (Turkey) [2], Senlis (France) [3], Segovia (Spain) [4], and Montemor-o-Novo (Portugal) [5]. These projects have sparked debates on best practices, challenges, and limitations, led by researchers, research centers, and international organizations such as ICOMOS [6]. The FRONTOWNS project: Think big about small border towns (PTDC/HAR-HIS/3024/2020) aimed to virtually reconstruct the urban evolution of Castelo de Vide (Portugal) and Cáceres (Spain), based on 3D modeling, to understand the role of these towns in the articulation of border territories between Portugal and Castile (13th-16th centuries). However, communication between the various fields involved, such as Archaeology, History, History of Urbanism, Design and 3D Modeling, presented significant challenges. To overcome these difficulties, a tailored methodology was developed, integrating the approaches of each field, facilitating communication among experts, and ensuring scientific rigor and quality in the digital reconstitution. The methodology followed the guidelines of the London Charter [7], the Seville Principles [8], and the recommendations of ICOMOS, ensuring the credibility of the reconstitution. Due to financial constraints, the project initially focused on the town of Castelo de Vide.

2 THEORETICAL BACKGROUND AND RELATED WORK

Digital reconstruction plays a crucial role in urban planning and military structures, filling gaps left by written or archaeological sources and enabling the testing of hypotheses. It provides the public with an immediate visual connection to the past, enhancing the perception of historical sites by recovering landscapes, building volumes, materials, and night scenes without electric lighting. In castles, a popular heritage site, it restores lost structures and reconstructs the civil and military dynamics of courtyards once filled with housing, stables, and storage spaces.

Several projects in digital heritage reconstruction have adopted diverse methodologies. Some [28, 29, 30] focus on 3D scanning combined with historical document analysis, while others [31, 32] start with hypotheses based on iconographies or archaeological artifacts before proceeding to modeling. A multi-step approach integrating historical and morphological analysis with topographic surveys and 3D scanning has also been used [33]. These methodologies often follow a structured, compartmentalized collaboration, which, while advancing historical site understanding, can limit deeper expert interaction.

The quality of virtual reconstructions depends on balancing historical accuracy with technical performance. VR and AR applications require optimized models with lower polygon density for interaction, while animations and static renders allow for high-resolution textures and complex lighting. If intended for 3D printing or real-time visualization, further optimization is necessary. When modeling historical figures, maintaining authenticity without compromising performance is essential.

3 MATERIAL AND METHODS

The methodology developed for the virtual reconstitution of Castelo de Vide was the result of intense multidisciplinary collaboration, involving experts from areas such as History, Archaeology, History of Urbanism, Design and 3D Modeling. This diversity of knowledge allowed the integration of technical and theoretical approaches, ensuring that methodological decisions were well-founded and that the reconstitution reflected historical rigor and technical precision. This methodology combined characteristics like those described by [1], integrating **bottom-up** and **top-down** approaches. The **bottom-up approach** is rooted in empirical evidence and refers to the use of data derived from the physical site itself. In the context of this project, it was based on the analysis of material evidence, including remaining architectural elements, archaeological records, and restoration data. This approach provided a concrete basis for mapping and identifying measurable structural aspects of the building, such as the dimensions and locations of existing walls, doors, and other architectural features. It is a method that prioritizes direct, tangible data, ensuring that the reconstruction remained grounded in the real, observable components of the heritage site. On the other hand, the **top-down approach** involves interpreting broader historical and contextual information, often derived from written or iconographic sources. In this project, the top-down approach incorporated interpretations based on historical texts, maps, and visual representations, which allowed the formulation of hypotheses to recreate missing or incomplete elements. For example, historical records and iconography were used to inform the reconstruction of architectural features that no longer existed or were not preserved, ensuring the reconstitution was contextualized in its historical setting. This approach helps to fill in gaps in the material record by considering what is historically and culturally plausible. Together, these approaches allowed for a balanced and comprehensive reconstruction process, ensuring both the accuracy of tangible data from the site and the historical authenticity of missing elements. Inspired by the methods of [9, 10, 1], the methodology was structured in four main steps:

1. **Scope & Collection:** Defining general and specific objectives, identifying limitations, and selecting appropriate tools and strategies. This stage involved collecting historical documentation, such as maps and engravings, and defining quality and accuracy criteria for the final products.
2. **Acquisition:** Obtaining the necessary data, including photogrammetric surveys, 3D scans, and field measurements. This phase was intrinsically linked to the beginning of the production process, favoring continuous validations and adjustments.
3. **Analysis & Interpretation:** Verification, validation, and integration of the collected data on an interpretative basis. This stage included formulating hypotheses for missing elements, identifying gaps, and proposing interpretative solutions, ensuring greater historical fidelity in the final modeling.
4. **Production:** Materializing the analyses through the creation of detailed models, developing visual narratives, and digital simulations that contextualize the models. The results were consolidated in formats suitable for scientific dissemination.

3.1 Scope

Virtual reconstitution projects usually focus on recreating tangible monuments, and benefited from advanced technologies such as virtual reality [11]. The FRONTOWNS project, however, adopted a broader approach, emphasizing mobility flows between border towns. This required defining essential elements, selecting **key points of interest (PoIs)**, and balancing historical accuracy with interpretive clarity. Documentary sources, including 15th- and 16th-century maps, historical records, and archaeological data, were crucial in analyzing urbanization and social dynamics. Despite gaps in housing typologies and socio-topography, these sources aided studies on trade, crime, and pilgrimage routes. The castle, a central element, required detailed investigations using military cartography, restoration reports, and architectural plans from the Castelo de Vide City Council (CMCV). Duarte de Armas' drawings (1509–1510), compiled in the *Book of Fortresses* [12], were fundamental, though critical cross-referencing with archaeological data revealed simplifications, such as the courtyard wall's depiction.

Initially, the virtual reconstruction followed ICOMOS guidelines, but emerging uncertainties led to a collaborative workshop[1] in an academic conference format. Experts in history, archaeology, design, and 3D modeling clarified key aspects, particularly regarding the historical period's impact and the need for interdisciplinary integration. Castelo de Vide retains much of its medieval layout yet defining an action plan proved challenging—not just reconstructing buildings but also integrating characters to enhance historical authenticity. Translating historical sources into virtual form raised questions about site and character selection,

[1] Workshop: Discovering the Small Border Towns: Sources for the Study of the Urban Landscape, Links and Flows. Held between May 26th and 28th, 2022 in Castelo de Vide.

prompting a second workshop to deepen the discussion on social and spatial dynamics.

3.1.1 Identifying the elements

To fill the gaps identified, align visions and strategies, and ensure consistent progress in the reconstitution process, a second workshop[2] was organized, this time of a practical nature, a co-creation workshop[3]. Aimed at producing narratives, the workshop used manipulative materials as a central tool to stimulate the creative process. As part of the playful dynamics designed to guide the construction of the stories, participants received cards representing characters and PoIs, as well as pins, markers, and other support materials. This collaborative approach was based on historical data, encouraging enriching and creative interaction among participants (Figure 2). The activity made it possible to map the flows of characters within the local geography and to develop scripts based on historical themes, such as plague, marriage, prison escape, and trade. The detailed analysis of the PoIs highlighted the castle as a central element, in addition to other significant components, such as the barbican, the wall, and the market space. However, gaps in the documentation required the use of historical analogies, allowing inferences based on contemporary constructions or similar contexts. This approach helped to define which characters and PoIs should be part of the reconstitution.
Through this activity, participants identified the central characters that should appear in the reconstitution, choosing not only the most common figures, such as nobles and peasants, but also figures representing the various occupations of the time, such as notaries, judges, artisans and muleteers, among others. PoIs were also defined, such as the castle, the town, churches and current houses, among other elements. In addition, historians identified animals that could be included in the virtual setting, contributing to authenticity and connection with medieval society.

Figure 2: Cards and supporting material used to assist in the creation of stories.

3.1.2 PoI Selection

To portray authentic daily activities fairgrounds were prioritized in the reconstitution due to their centrality in medieval towns and their ability to integrate diverse characters into the setting. Strategically located in front of the castle, the fairgrounds also facilitated the creation of narratives that reflected the interactions and social flows of the time. The stories created were essential for identifying and mapping these routes, highlighting the dynamics of circulation and connection between different PoIs. However, the dispersion of some routes to areas distant and disconnected from the castle led to the need to delimit a more compact geographic area. This decision was made jointly by historians and designers. The historians based their analysis on the greater concentration of events reported in historical documents, while the designers considered the complexity of including all the elements in the virtual reconstitution. Based on these complementary contributions, the following priority PoIs were defined (Figure 3):

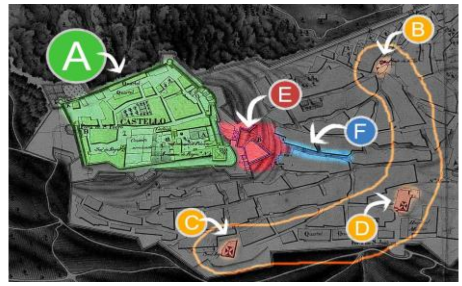

Figure 3: Diagram prepared by the author, with PoIs identified.

(A) Castle complex, including the keeper, wall and the fortified settlement featuring its Main Street.
(B) Town fountain;
(C) Church of Santiago;
(D) Church of São João;
(E) Fair;
(F) Santa Maria Street.

Due to the impossibility of including all the elements mentioned, some of them, such as the fountain (B) and the churches (C, D), were discarded because they were located too far from castle (A). This decision was motivated by the complexity of some of these points, which would require additional time for modeling, which would compromise the time available for creating the main PoIs. The fair (E) was chosen as the place where the characters congregate the most, and Santa Maria Street (F) was included because it is the main access route to the castle and its toponym is mentioned in several historical documents from this period. The inclusion of this street was considered sufficient to represent the types of houses of the time, incorporating typological variations based on historical information and comparative analyses, making the inclusion of all the houses unnecessary. This approach allowed us to optimize the time and resources available, focusing on the most representative and significant elements for the construction of the scenario. The team, in a multidisciplinary way, even reaching interdisciplinarity in certain phases of the process, carried out a careful analysis of the factors that would influence the modeling of the environment. Historians and 3D designers worked together to assess both the need for character movement and the level of detail required for the 3D models. The historians provided detailed information about the space and social dynamics of the time, helping to determine which areas and elements should be highlighted in the reconstitution. The multimedia creators considered the Level of Size (LoS) of the environment [13] and the Level of Detail (LoD) of the 3D model [14], analyzing the technical limitations of time and resources. The collaborative work between the teams made it possible to balance the size of the environment to be modeled with the need to ensure an adequate level of detail. This multi and interdisciplinary approach was essential to define the scope of the modeling, ensuring that both historical accuracy and technical feasibility were met. In this sense, a priority scale was

[2] Workshop: Development of strategies for creating a digital story co-creation tool - Held on November 4, 2022 in Coimbra.

[3] Co-creation workshop based on the method described by: Van Zeller, M. (2022). Jogos com realidade aumentada nos museus (J. Ferreira, Ed.; Coord. científica C. F. Camacho, 1ª ed.). Lisboa: Caleidoscópio: Património Cultural. (Estudos de museus).

created for the elements (Table 1), aiming to align the modeling of the different points of interest with their level of historical importance and the time available for development. The LoD directly impacts the result, since the complexity of the modeling varies according to the type of structure. More imposing structures, such as the castle, require a greater level of detail, while elements of the urban core can be represented with a different LoD, more appropriate to their function and visibility in the context of the reconstitution.

Table 1. Organization and prioritization of 3D elements, level of detail and LoD scale.

Modeling priority	3D Element	LoD (1 a 5)
1	Topography	5
2	Castle	5
3	Alcaides' Palace	5
4	Keep	5
5	Walled Fence	4
6	Wall Gate	5
7	Fair	4
8	Pelourinho (pillory)	5
9	Characters	4
10	Settlement with its Main Street	3
11	Santa Maria Street	3
12	Animals	2
13	Fair Objects	2

Table 1 organizes and prioritizes the elements to be modeled in 3D, assigning each one a LoD level from 1 to 5, according to its importance. The topography, being fundamental to the spatial configuration and authenticity of the reconstitution, received the highest LoD (5), as did other central elements, such as the Castle, the Alcaides' Palace, the Keep, the Wall Gate and the Pelourinho (pillory). The latter, due to its symbolic relevance. Elements of intermediate importance, such as the Walled Fence and the Fair, were classified with LoD 4, while the Burgo with Main ("Direita") and Santa Maria Streets received LoD 3, focusing on the general representation of the houses and streets. Items with less visual or narrative impact, such as Animals and Fair Objects, were assigned LoD 2, balancing technical effort and functionality. This structure helped to optimize the modeling and ensure coherence between the project objectives and the available resources.

3.1.3 Reconstitution Format

The main project challenge was not the identification of the elements or the study of historical sources, but rather choice of approach for the reconstitution. In addition to the technical challenges involved in the 3D reconstitution, it was essential to define the final format of the project, ensuring that the focus was on its educational character. This challenge arose due to the complexity of reconciling the objectives of the project with the technical limitations and the different forms of representation. Several possibilities were evaluated, including illustrations, infographics, films, animations and interactive elements, and it was necessary to consider the impact of each of these approaches on the way in which the information would be transmitted to the public. Initially, the development of a system in the format of a 3D game, based on virtual choreographies [15], was considered, which would allow teachers to present historical events in a dynamic way. However, although the process of creating narratives was highly productive and enriching, concerns arose about possible scientific distortions, which could divert the focus of the historical reconstitution, which was based exclusively on documentary sources. To avoid these risks, it was decided that the final product would be a 3D animated video in walkthrough format, with a predefined path, inspired by a narrative that portrayed an ordinary day at the time. In this way, it aligned with the Seville Principles, which highlight data transparency and testability as essential requirements, ensuring that the results can be evaluated and validated by other researchers. Although the animated video was chosen as the final format, this decision did not rule out the possibility of exploring other interactive modalities in the future.
The dialogue between historians, historians of art and urbanism, archaeologists and designers was crucial to balancing academic expectations with the practical limitations of the project, adjusting the methodological approach to meet the demands and operational conditions.

3.2 Acquisition

This stage, of an eminently practical nature, is intrinsically linked to the initial production phase, especially due to the need to make continuous adjustments and validations of data directly in the field.

3.2.1 Topography

Castelo de Vide is a Portuguese town in the Alentejo region. Its topography was the main practical project challenge, due to its peculiar and complex configuration. With a narrow and winding shape, the town is located between flat landscapes with low hills and the surrounding mountain range (Figure 4a). The buildings, including the castle, were built according to the natural elevations of the topography, which is reflected not only in the urban fabric, but mainly in the arrangement of the different volumes of the castle, which follow the winding alignment of the relief. The specific topography of the castle area, located on a ridge, presents variations of up to 10 meters in a single street (Figure 4b), which represented a significant challenge for the modeling of the area.

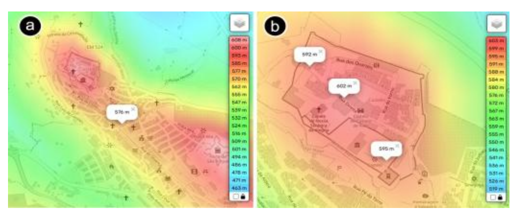

Figure 4: (a) Topographic map of part of the urban area. (b) Detail of the topography of the castle area.

Given the absence of detailed topographic mapping, a photogrammetric[4] study was carried out, through the combination of multiple sources, with the aim of generating a 3D mesh of the topography. This process involved combining three main sources: the general plan photogrammetry created by Andrea Spohnetta, made available under a Creative Commons license (CC BY-NC 4.0) on Sketchfab (https://sketchfab.com/spogna), the 3D topography obtained from Cesium ion for Unreal Engine (https://cesium.com/platform/cesium-for-unreal/), and the Google Earth maps (https://earth.google.com). Although the castle area, located at the top of the relief, appeared flat at first glance, detailed analyses revealed a system of distinct topographic levels. The sources used to construct the topography did not reflect this

[4] Photogrammetry is a technique that consists of creating 3D models from a set of geolocated and parameterized photographs, using mathematical techniques such as triangulation.

characteristic, presenting the elevated area in a simplified form, with predominantly flat faces (Figure 5a). This observation was made possible through in situ measurements, analysis of satellite data, and drone images. Due to the limitations of the sources, manual and artistic modeling was necessary to recreate the topography, which required considerable time and human resources, including several on-site visits for detailed analyses and additional measurements, as can be seen in Figure 5b, compared to the current view from the same angle. Although the work was predominantly technical and depended on equipment and computer skills, historians and archaeologists closely monitored the process. Collaboration was essential to adjust the historians' expectations, considering the practical limitations and challenges faced.

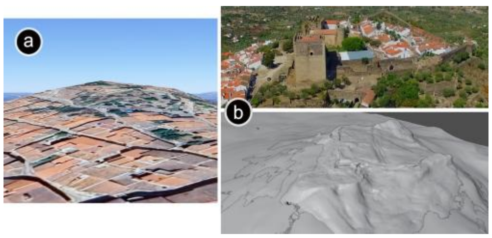

Figure 5: (a) Topography presented by Google Earth. (b) Comparison between the current construction and the 3D modeled topography.

3.3 Analysis and Interpretation

Based on data collected and the LoD assigned to each element, the sequence of efforts for the reconstitution was established. The first step was formulating the hypothesis of reconstructing the castle complex, followed by reconstructing the other elements, respecting the LoD sequence. After that, the composition of the characters' costumes was discussed, considering the specificities of the period. The houses located on Main Street (inside the walls) and Santa Maria Street (on the outskirts) were classified as having an intermediate LoD and were left in the background, prioritizing the modeling of the castle complex. The definition of the fair's objects and their composition was analyzed based on several sources, considering the typical products of the time and the specific location. To support the formulation of the hypothesis of reconstructing the castle and other structures in the previously established period, three main sources of analysis were considered: **the current reality**, the **iconography/documents** of the time, and **references from other national monuments** of the same period. From these sources, guidelines were established that served as practical strategies in the process of formulating hypotheses for the 3D reconstitution of cultural heritage:

- If the element exists physically and corresponds to iconography, consider it as the primary reference.
- If the element exists physically but has undergone significant modifications over time, it should not be considered as the primary reference. In this case, the iconography and documents of the period should be prioritized.
- If the element does not exist physically, use the iconography and documents of the period as a reference.
- If there is archaeological correspondence with the iconography, but the element does not exist physically, the archaeological correspondence should be used as the primary reference.
- If there is not enough iconography to clarify doubts about elements, use references from other national monuments of the same period.
- In the absence of national monuments, archaeological remains or reliable iconography, the element will not be considered in the reconstitution.

The process of developing the reconstitution hypothesis was marked by a constant exchange of information and debates between historians, archaeologists and the modeling and design team, always considering the established guidelines. This collaborative work was essential to ensure historical loyalty, requiring everyone, especially the design team, to clearly understand the decisions made. The complexity of the process lay in the interpretation of elements that were missing or modified over time, which required that each decision be well documented and explained to be translated into accurate 3D models. This required greater attention to the nuances of interpretations and clear communication between the parties, respecting the limitations of digital modeling. To facilitate communication and ensure uniform understanding, a practical co-creation workshop[5] was held, the objective of which was to collaboratively create a physical model representing the castle reconstitution hypothesis. The model would help to visualize the proportions and spatial relationships between the elements, in addition to serving as a tool to validate the choices made during the process of formulating the hypotheses. The basis for the construction of the model was a cadastral plan provided by the CMCV, with a scale of 1:10,000, which detailed the precise location of the spaces and buildings. Using materials such as paper, glue and pens, the team built the model, which, although based on a flat shape that did not reflect the real geography, served as a starting point for digital modeling, validating and adjusting the data before its digitization (Figure 6).

Figure 6: Workshop with the process of creating a physical model.

3.4 Production

The production stage involved 3D modeling of the main historical and social elements of Castelo de Vide, with different levels of LoD and methodological approaches based on archaeological, documentary, and iconographic evidence. Production began with modeling of the castle, using its current configuration as a basis and implementing historical changes suggested by historians. Due to the complexity of the castle's shape, which followed the sinuosity of the topography, we scanned the structure using an iPhone 11 and Scaniverse software (https://scaniverse.com) surveying in separate

[5] Workshop: Analysis and prototyping of the castle, wall and medieval town of Castelo de Vide for 3D modeling - Held on December 2, 2022 in Coimbra.

parts, with geolocation, to generate 3D meshes with precise heights. This allowed the creation of a library of representative elements and a geolocated guide mesh, which was later refined in Blender 3D (https://www.blender.org/). In situ measurements with a laser meter were also performed to ensure the accuracy of the modeling, correcting for height variations caused by the sinuosity of the topography (Figure 7).

Figure 7: Comparison between the 3D guide mesh and the real image of the wall.

The virtual reconstitution of the Keep, partially destroyed and rebuilt in the 20th century, was based on the configuration found in the iconography. The modeling of symbolic elements, such as the pillory, was carried out with a high level of detail, based on iconographic representations and analysis of physical remains of pillories in contemporary towns. For the fair scene, some objects were modeled based on instructions from historians, while others were acquired from 3D asset marketplaces and adapted according to the specificities of the location, respecting the visual standard of the time. Since the fair was a multifunctional space that integrated commerce, production and festivities, objects based on archaeological findings, such as utensils and ceramics, were incorporated to reinforce the authenticity of the scene and represent everyday practices, such as the sale of products and artisanal production (Figure 8).

Figure 8: (a) Allegory of a medieval fair. (b) Archaeological finds from excavations at the site. (c) 3D reconstitution of the fair space.

Since the focus of the project was on the reconstitution of everyday dynamics, and not just on architectural elements, it was essential to populate the scene with human and animal characters to create a historically plausible environment. Characterization of the characters, however, presented challenges, especially in terms of historical fidelity, due to the risk of inaccuracies. The first step was to select the most relevant figures and analyze documents, iconography and publications to guide the modeling [16, 17]. Unlike the modeling of the fair, the characters were mostly modeled, with the acquisition of some additional 3D modeling packages, especially for the inclusion of animals. The focus on the characterization of the characters was their clothing. As indicated by historians, who provided extensive iconographic sources, it was observed that the characters portrayed, including nobles, officials, peasants, artisans and merchants, among others, were depicted in clothing that reflected their respective social classes and functions. Nobles and officials were dressed in elaborate clothing made of dyed fabrics and adorned with distinctive accessories. In contrast, peasants wore simple clothing made of wool or linen in natural tones, while artisans and food merchants were dressed in attire suited to the practical demands of their trades. In addition to clothing, details such as hats, footwear and ornaments were considered in the modeling, as well as tools and objects characteristic of each trade (Figure 9). Animals, frequently depicted in the iconography of the time, were also included, standing out not only as decorative elements, but with a symbolic role in medieval daily life.

Figure 9: (1) Clothing of authorities. (2) Clothing of peasants. (3) Butcher. (4) Left reference, right 3D reconstitution (Coif, Nobleman's hat, Shoes).

The modeling of the houses on Main Street and Santa Maria Street followed LoD 3, with a moderate level of detail. The volume of the buildings was simplified, focusing on external elements such as windows and doors, while the interiors were not modeled. Texturing was the main resource used to provide realism and highlight architectural features. Comparisons were made with buildings from other contemporary towns, as well as with photographic references of houses in the region, to ensure greater historical fidelity. The modeling also considered regional characteristics, such as shorter eaves adapted to the dry climate of the area and the variety of ogival doors, from the simple to the more ornate.

4 UNCERTAINTY MAP

The final modeling step, as observed in related projects such as Évora [18], Ávila [19] and Montemor-o-Novo [5], included the application of a color scale of historical-archaeological evidence, following the work of [20]. This approach was used to clearly communicate the degree of verisimilitude of the Reconstruction Units in the virtual model, allowing the public to understand the sources and levels of certainty involved. The color scale follows the traditional convention, where warm colors indicate greater authenticity, and cold colors reflect greater uncertainty or hypothetical character. However, in projects such as Milicz [21] and Messina [22], the conventions were adapted according to the specific needs of each work. In the case of Castelo de Vide, the scale was organized as follows:

- Gray (#808281) (Imagined): Elements based on historical and natural approximations.
- Dark blue (#004594) (Similar structures): Elements based on comparisons with other similar structures or architectural elements from the period or region.
- Light blue (#5FC3E1) (Textual reference): Elements based on textual references from historical sources.

- Green (#A2C516) (Graphical reference): Elements based on graphic representations, such as drawings, engravings or paintings from the period.
- Yellow (#FFE500) (Archaeological information): Elements based on archaeological data, such as reports, photographs, plans or drawings.
- Pink (#EE7883) (Modification of existing): Structures or elements that exist in a partial or modified form.
- Red (#B61918) (Existing as original): Structures or elements that remain as they were in the past, without alterations.

Figure 10 illustrates the application of the scale, highlighting the different levels of authenticity and the sources used in the reconstruction. The Keep, for example, exemplifies the application of scale, with the walls represented in red and pink (indicating preserved and modified areas), the door and windows in yellow (based on archaeological information) and the top of the tower in green (recreation based on graphic references, such as drawings and paintings). This uncertainty map allows the public to understand the complexity of the reconstruction and the sources that support each modeling decision, offering a transparent view of the process.

Figure 10: Chromatic scale of historical-archaeological evidence applied to elements of 3D reconstitution.

5 Complexity Scale for 3D Models of Cultural Heritage

Based on the challenges faced during modeling, especially regarding topography, a complexity scale was developed for the 3D development of cultural heritage sites, considering aspects such as topography, geolocation and structural context. This scale reflects the different relationships between the monument and its surroundings, facilitating the understanding of the technical and conceptual requirements for the 3D modeling of cultural heritage sites. It is worth noting that it only aims to summarize common factors in this process, emphasizing the interaction between the monument and the context in which it is located, without considering the intrinsic complexity of the monument itself.

The first category**, Isolated Element (a)**, includes examples such as sculptures and artifacts, which can be recreated virtually without the need for territorial contextualization, preserving their original meaning, as in the Recording Michelangelo's David project [23]. The second, **Isolated Monument (b)**, refers to structures such as churches or houses, which, although linked to their original space, can be displayed in isolation, such as the 3D modeling of the Church of Panagia Ekatontapiliani, in Paros, Greece [24][25]. The third, **Topography as a Main Element (c)**, focuses on areas such as archaeological sites or natural formations, where virtual recreation only makes sense within the context of the topography itself, such as the virtual tour of the oppidum of Ulaca, Spain [26]. Finally, **Integrated Monument and Topography (d)** addresses monuments such as castles or fortified cities, which depend on interaction with topography to have their meaning and be historically reconstructed, as in the case of the royal gate of Seville in Spain [27].

6 Discussion

The virtual reconstruction methodological approach combined the current state of buildings, photogrammetric surveys, 3D, archaeological evidence, and historical and iconographic sources. This structuring the reconstruction hypothesis, based on a specific period, filling knowledge gaps and recreating missing elements. However, the interpretation of the data was challenging, especially when the iconographic representations did not correspond to the actual findings. For example, the analysis of historical drawings, of an artistic nature, required a balance between historical fidelity and spatial coherence. In Figure 11b (green), disproportionate or stylized elements made it difficult to accurately define the actual dimensions. Furthermore, in the same figure, some represented elements (in pink) did not match the physical findings. In cases where represented elements no longer physically existed, the archaeological discoveries revealed contours or features that contradicted the iconography, as shown in Figure 11b (yellow). When there was a discrepancy between iconography and archaeological findings, priority was given to physical evidence, in accordance with established methodological guidelines.

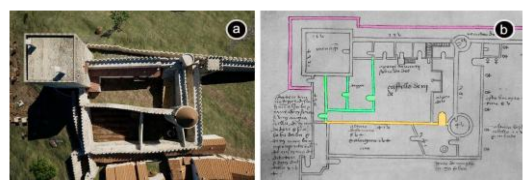

Figure 11: (a) 3D model of the Castle. (b) Plan highlighting inconsistencies identified in the analysis process.

One of the most significant innovations of the project was the implementation of co-creation workshops with stakeholders, allowing the collaborative construction of reconstruction hypotheses. These workshops involved experts in history, archaeology, modeling, technology, design, as well as university professors, doctoral students and the local community. The methodology adopted was essential for the development of the project, especially in the ideation. During the workshops, manipulative materials were used to record ideas, promoting a dynamic exchange of knowledge between disciplines. The visual outputs generated, such as sketches and brainstorming sessions, were fundamental for the ideation and as organized documentation for the entire team. The workshops also defined the elements of the reconstruction, promoting an exchange between historians, archaeologists, designers and other participants. Collaboration between the teams of historians and designers, who had to overcome limitations and prejudices, was essential to ensure that decisions were informed by both historical accuracy and technical feasibility. This joint effort resulted in creative and innovative solutions, ensuring that the reconstruction was both historically accurate and technically feasible. 3D modeling revealed the need to adapt time and resources to the different levels of complexity of the elements to be recreated. To this end, an initial classification was developed that established the levels of detail, allowing for a more structured and efficient approach. This classification was made possible by the creation of a complexity scale, which organized the elements into work batches and guided bibliographic research and best practices for their reconstruction. Modeling smaller elements, such as objects and characters, although less challenging than large structures, required considerable effort to ensure historical accuracy. The migration from Unity (https://unity.com) to Unreal Engine (https://www.unrealengine.com) aimed to increase visual realism, allowing the use of advanced resources such as MetaHumans and Mixamo (https://www.mixamo.com/) for animation. The choice of presentation format, focused on scientific and accessible visualization, was fundamental to the integrity of the representation. The quality of the preliminary results was considered excellent, in line with the initial objective of the visualization proposal, which sought to provide high-quality textures for buildings and expressive characters. Similar projects, such as the revitalization of Antioch, followed a similar approach, using real-time rendering engines to create environments rich in detail, but optimized to ensure fluid interaction, especially in character modeling (Figure 12).

Figure 12: Shop buildings with Roman architecture - Virtual Antioch.

The project remains open to exploring other tools and formats, such as the initial proposal to create narratives based on virtual choreographies, with the quality of the result depending on the specificities of each format.

7 Conclusion

The virtual reconstruction of Castelo de Vide, as part of the FRONTOWNS project, represents a milestone in the integration of collaborative and interdisciplinary methodologies, involving experts from the fields of humanities, arts and digital technologies. The main contribution of the project lies in the innovative methodology of co-creation workshops, which offers an inclusive, collaborative and dynamic approach to historical reconstruction. By integrating the perspectives of different disciplines and the local community, the project demonstrates how active collaboration can transform preservation processes, ensuring not only the technical accuracy but also the cultural relevance of the reconstruction. The combination of bottom-up and top-down approaches was fundamental to creating a faithful representation of the medieval city, with photogrammetric surveying and 3D scanning ensuring the accuracy of the preserved structures and historical and iconographic sources allowing the recreation of missing elements.

Supplemental Materials

All supplementary materials are available at https://drive.inesctec.pt/s/wxZy29kq3DcaPqG. This repository includes all images featured in the article and an additional set of images showcasing details of the 3D modeling, scanning processes, and co-creation workshops.

Figure Credits

Figure 1 image credit: Author
Figure 2 image credit: Author
Figure 3 Based on the map of the square of Castelo de Vide (Folque, Pedro et al., 1818). Source: Digital Library of the Portuguese Army: 3641/II-3-36-49. Available at: http://id.bnportugal.gov.pt/bib/rnod/268183
Figure 4 image credit: https://pt-pt.topographic-map.com/
Figure 5 image credit: (a) https://earth.google.com (b) Author.
Figure 6 image credit: Author
Figure 7 image credit: (a) Author (b) CMCV
Figure 8 (a) *Le Chevalier errant* (detail) - Thomas de Saluces, 1403-1404. Source: gallica.bnf.fr. (b) Archaeological findings (CMCV). (c) Author.
Figure 9 image credit: (1)(2)(3) Author. (4) *(Coif) Parables of the Blind* (Detail) - Pieter Bruegel (1568). Capodimonte Museum, Naples; *(Nobleman's Hat) Apresentação no Templo* (Detail) - Vasco Fernandes (1501-1506). National Museum Grão Vasco, Viseu; *(Shoes) Fuga para o Egipto* (Detail) - Vasco Fernandes (1501-1506). National Museum Grão Vasco, Viseu.
Figure 10 image credit: Author
Figure 11 image credit: (a) Author. (b) Figure based on an engraving by Duarte de Armas [12].
Figure 12 image credit: Figure from [34].

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