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CRAFTING AND MODIFYING RHINE CASTLE MODELS WITH PARAMETRIC MODELING IN BLENDER

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ABSTRACT:

In the domain of architectural heritage conservation, the recent advancements in 3D modeling have significantly improved the reconstruction fidelity of historical edifices, particularly medieval castles of the Rhine region. The existing traditional 3D modeling methodologies, though precise, are laborious and exceedingly time-consuming, requiring a detailed focus on intricate architectural nuances. Advancements in Building Information Modeling (BIM) technology have played a key role in simplifying this process, offering an adaptable and parametric approach to architectural modeling. Nonetheless, the domain of Historic Building Information Modeling (HBIM) faces the distinctive challenge of scarce parametric object libraries that are suitably representative of historical heritage, compounded by the architectural heterogeneity inherent in these ancient structures.
This paper presents a novel methodology utilizing the Blender software suite, with an emphasis on exploiting "Geometry Nodes" and "Modifiers" for parametric modeling. We introduce a technique that significantly enhances the efficiency of modeling Rhine castles. This method supports rapid alterations and precise customization, catering to the specific analytical needs of archaeologists and heritage researchers. The proposed approach aims to bridge the gap in HBIM by providing a flexible, dynamic toolset for the accurate digital preservation of historical architecture.

1. INTRODUCTION

1.1 Historical and heritage context of Rhine castles

The Rhine River, an important waterway in Europe, is home to many medieval castles along its banks. These castles are key markers of Europe's history and strategic importance. Initially built for defense, these structures later became symbols of power. Over time, they have undergone destruction and restoration, resulting in a mix of architectural styles. The preservation of these castles, often hindered by a lack of original blueprints, is greatly aided by modern 3D modeling techniques like HBIM and parametric modeling. These tools are crucial for keeping their cultural heritage alive and intact.

1.2 Challenges in 3D modeling of Medieval Heritage

Medieval heritage presents unique challenges in 3D modeling due to the distinctiveness and complexity of each structure. Unlike modern buildings, medieval structures, like castles and cathedrals, require individualized modeling approaches. This complexity is compounded by their semantic and geometric subtleties, necessitating specialized parametric libraries that accurately capture historical styles and construction methods. These libraries must also account for various historical modifications, blending different styles and materials.

1.3 Objectives and scope of the study

This study aims to utilize Blender (Blender Foundation, 2023), a sophisticated 3D modeling software, to create a versatile and detailed model of Birkenfels Castle, shown in Figure 1 and referenced from (Visitgrandest, 2024). Focused on hand-modeled elements reflective of medieval architecture, the project employs Blender's tools like Geometry Nodes and Modifiers for parametric modeling. This approach allows for adaptable structures that can be modified in size, shape, and style, aligning with various scenarios and interpretations of the castle's history.
The parametric nature of the model is central to its adaptability, facilitating changes based on new research or different reconstruction hypotheses. Although the main focus is on the Birkenfels Castle, the methods and knowledge gained from this project are designed to be applicable to a wider range of heritage conservation efforts. This project demonstrates Blender's effectiveness in parametric modeling of medieval heritage, aiming to offer tools and methods applicable to a diverse range of historical structures. In sum, the study combines traditional 3D modeling with innovative approaches required for medieval heritage conservation, contributing to the digital reconstruction and preservation of historical sites.

2. RELATED WORKS

2.1 Literature review on HBIM and parametric modeling

In heritage conservation, Heritage Building Information Modeling (HBIM) and parametric modeling are crucial for documenting and reconstructing medieval heritage. These structures, with their complex details and styles, require semantic-rich digital representations. This approach captures more than geometry; it highlights the historical and architectural essence of each element. De Luca et al. (2007) and Remondino et al. (2012) have emphasized the creation of libraries of elements and primitive-based 3D modeling, focusing on the semantic understanding of architectural elements, underscoring the need for a comprehensive approach that blends the geometric fidelity with rich historical insights.

Figure 1. Aerial view of the current state of the Birkenfels Castle

The challenges in applying BIM to existing buildings, particularly historic structures, are manifold, including high modeling costs, data uncertainty, and the necessity for detailed levels of data capture. Volk et al. (2014) and Banfi et al. (2017) highlight these specific challenges, addressing the need for intricate data capture techniques such as photogrammetry and 3D scanning to create accurate and informative models. The detailed level of documentation required for these buildings is not just for preservation but also for understanding the historical context and enabling accurate reconstructions.

Furthermore, the parametric modeling approach is advancing the field of heritage conservation by facilitating the management of complex morphologies through adaptable and dynamic modeling approaches. Banfi (2016) and Murtiyoso et al. (2018) have demonstrated the potential of integrating advanced 3D surveying techniques with parametric modeling. This approach is particularly beneficial in managing the morphological complexity of historical buildings, facilitating the conservation and restoration efforts by adapting the models according to new findings or hypotheses.

The integration of HBIM with ontological frameworks and 3D GIS, as proposed by Dore and Murphy (2012) and Yang et al. (2019), represents a significant advancement in enriching the semantic understanding of heritage sites. This integration not only enhances the geometric detailing but also enriches the models with semantic and historical information, providing a holistic view of the heritage site that combines geometry, semantics, and historical data. Such enriched models are invaluable in the management, analysis, and interactive exploration of cultural heritage sites.

The significance of structural health monitoring and simulation in safeguarding heritage buildings is profoundly acknowledged. The systematic transformation of BIM models into finite element models is crucial in structural simulations that support the building’s authenticity and ensure its structural integrity. This facet is fundamental to the enduring preservation and safety of heritage structures, representing a domain where the fusion of contemporary technological advancements with age-old conservation methods offers immense potential.

In summary, the literature reflects a growing recognition of the need for detail-oriented and flexible modeling frameworks capable of accommodating the unique challenges of heritage modeling. The integration of geometric details with rich semantic and historical data is not merely a technical aspiration but a necessity to preserve, understand, and share the legacy of these cultural assets. As technology advances, the ability of these tools to change and meet the requirements of preserving cultural heritage also grows. This ensures that historical structures are maintained not just in their physical shape, but also in their essence and historical context.

2.2 Existing 3D modeling techniques for Heritage

The advancement of 3D modeling techniques has significantly impacted the preservation and documentation of cultural heritage, offering a detailed and semantically enriched representation of historical structures. Key to this development is the application of Historic Building Information Modeling (HBIM), which provides a nuanced approach to capturing the unique characteristics and irregularities inherent in ancient buildings. The adoption of diverse and adaptable 3D documentation methodologies is advocated by Murtiyoso et al. (2018), who suggest a multi-sensor and multi-scale strategy. The integration of dynamic parametric modeling with 3D surveying techniques, crucial for the conservation and restoration of historic buildings, is highlighted in Banfi (2016). Further, the fusion of HBIM with other technological innovations such as 3D GIS, as noted by Dore and Murphy (2012), extends the potential for a comprehensive analysis and management of heritage sites. This collaboration successfully connects parametric CAD modeling with

geographic information systems, helping to better preserve and understand heritage buildings.
The fidelity and authenticity of heritage sites are meticulously maintained through parametric tools and semantic modeling. Chevrier et al. (2010) illustrate the application of parametric modeling in the virtual 3D reconstruction of architectural details, ensuring that any intervention remains congruent with the historical and architectural context.
Focusing on the Rhine Castles, various studies have demonstrated the use of different 3D modeling software to document the unique and intricate features of these monuments. Benazzi (2018), Heitz (2023) and Rigaud (2023) have employed Sktechup, Maya and Blender respectively. This illustrates the flexibility and adaptability of multiple tools in effectively capturing and representing the complex aspects of such heritage sites.
The literature underscores the necessity of a dual approach in employing HBIM and parametric modeling to effectively manage and preserve cultural heritage. The technological strides in this domain permit more precise, detailed, and semantically rich portrayals of historic buildings. Coupled with integrations such as GIS, these advancements enhance the ability for detailed analysis, management, and conservation planning of cultural heritage sites. The collaborative utilization of varied 3D modeling tools and techniques is imperative for safeguarding the historical and architectural essence of significant structures, including the Rhine Castles.

2.3 Gaps and opportunities in current methods

In the field of heritage conservation, the adaptation and application of Heritage Building Information Modeling (HBIM) and parametric modeling have been at the forefront of addressing the unique complexities and conservation needs of historical structures. These methodologies are essential for preserving the intricate details and varied styles of medieval heritage, demanding a sophisticated approach that combines geometric reconstruction with rich historical insights.
Barazzetti et al. (2015) draw attention to the specific challenges posed by historic buildings, which often feature complex forms, heterogeneous materials, and morphological modifications. They advocate for advancements in automatic recognition of different elements, a solution that could significantly streamline the modeling process. Yang et al. (2019) suggest the potential for automatic segmentation of meshes to create better models based on geometric primitives, addressing the difficulty of extracting these primitives from complex structures.
The need for comprehensive and systematic modeling knowledge, particularly in the context of conservation, is underscored by Remondino (2011), who points out the lack of systematic modeling approaches in the field. This observation is supported by Garagnani and Manferdini (2013), who discuss the difficulty of extracting characteristic elements from dense point clouds due to the complexity of the data involved. Aicardi et al. (2018) emphasize the necessity of ensuring accuracy between field surveys and modeled data, a crucial aspect of preserving the authenticity and integrity of heritage structures.
Boeykens (2011), Banfi (2017) and Banfi (2020) further discuss the importance of creating lightweight models that are easily manageable and the need for high precision in modeling complex forms. They highlight the need for adaptive levels of detail that align with the context and requirements of each project, emphasizing the importance of precision in models to closely reflect reality. Similarly, Remondino et al. (2012) focus on the importance of lightweight models for effective manipulation and visualization, addressing the need for practical, user-friendly solutions in the preservation and study of heritage buildings.
Finally, Rocha et al. (2020) draw attention to the difficulty of the scan-to-BIM process, which requires a comprehensive set of skills throughout the workflow. They advocate for improved training and development in this area, indicating a broader need within the field for enhancing the capabilities and understanding of professionals involved in heritage conservation.
While the challenges in HBIM modeling are significant and multifaceted, the literature suggests several potential solutions and areas for further development. These include the need for automation in the reconstruction of architectural forms, improved data transfer and processing, and the development of lightweight, accurate models. As the field continues to evolve, these advancements will play a crucial role in the ongoing efforts to preserve and understand our rich architectural heritage. Furthermore, 3D modeling software such as Blender or Maya is increasingly being recognized for their role in heritage conservation. Their user-friendly interface and powerful modeling capabilities make them valuable tools for creating detailed and immersive representations of historical sites. These software are not only efficient in use but also incredibly useful for public dissemination and educational purposes, providing interactive and engaging ways to explore and understand cultural heritage. However, it is also acknowledged that while these general 3D modeling tools excel in visualization and flexibility, they may lack some of the robust data management and semantic capabilities inherent in BIM software specifically designed for HBIM. As such, there’s an ongoing need to balance the strengths of different types of software to fully harness the potential of digital technologies in the field of heritage conservation.

3. METHODOLOGY

3.1 Introduction to Blender

Blender is a powerful tool in the realm of 3D heritage modeling, praised for its versatility and broad application range. As a free, open-source software, Blender empowers a diverse community of users, from professional architects and archaeologists to hobbyists, to create detailed and accurate representations of cultural heritage sites. Its comprehensive suite of features supports a wide array of tasks essential in heritage modeling, including photorealistic rendering, sculpting, and virtual reality simulations. The open-source nature of Blender encourages users to develop and share plugins, continually enhancing the software’s capabilities and making advanced techniques more accessible. This collaborative environment is particularly beneficial for the field of heritage conservation, where resources and knowledge are often shared globally. Blender’s ability to produce high-quality models, combined with its cost-effectiveness and strong community support, makes it an increasingly popular choice among professionals and enthusiasts in the 3D modeling of heritage sites. As the field evolves, Blender continues to facilitate the detailed preservation of the cultural legacy.

3.2 Description of Geometry Nodes and Modifiers

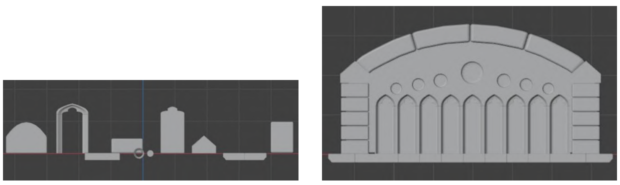
In 3D heritage modeling, Blender’s Geometry Nodes system serves as a groundbreaking feature for creating sophisticated, parametric designs. Essentially, Geometry Nodes is a procedural and node-based workflow that allows users to construct complex geometry using a series of interconnected blocks, or ”nodes.” Each node performs a specific function - be it creating shapes, transforming geometries, or replicating patterns. By connecting these nodes, users can build intricate and customizable structures. This is particularly advantageous in heritage modeling where reproductions of complex architectural elements, such as ornate carvings or period-specific architectural features, are needed. The procedural nature of Geometry Nodes means that once a node setup is created, it can be saved and reused, making the process of modeling repetitive or patterned elements more efficient and less prone to human error.

Alongside Geometry Nodes, Blender’s Modifiers further enhance the capability for intricate and accurate modeling. Modifiers are tools that affect the geometry of an object in a non-destructive manner. They can be used to smooth, bend, twist, and otherwise alter models, all while maintaining the original mesh intact. This aspect is especially useful in the iterative nature of historical reconstruction. As discussions with historians and archaeologists evolve, models often need to be adjusted or refined. With Modifiers and Geometry Nodes, these alterations can be made swiftly and efficiently, allowing for rapid iteration and refinement of models based on scholarly feedback.

Together, these tools significantly streamline the workflow of heritage modeling. The use of Geometry Nodes and Modifiers not only makes the initial creation of complex models more manageable but also ensures that subsequent iterations, often necessary in the collaborative and iterative nature of historical reconstruction, are done with ease and precision. This capability is particularly beneficial when working closely with historians and archaeologists, as it allows for the seamless incorporation of new insights or discoveries into the 3D models, ensuring that the final reconstructions are as accurate and detailed as possible.

3.3 Parametric modeling process: From design to implementation

Parametric modeling of architectural objects entails an initial manual modeling of each critical component, which then allows for the subsequent application of Geometry Nodes and modifiers to duplicate and deform each element to achieve the desired result. Furthermore, to obtain the exact dimensions of the object to be modeled, it is essential to use data from laser scanning, tacheometry, or photogrammetry, depending on the structure’s complexity. Here, by figure 2, we present a bay with trilobed lancets and seven oculi present on the Wasenbourg Castle located near the town of Niederbronn, Alsace, France.



(a) Basic elements sculpted manually prior to parametric manipulation

(b) Synthesis of Geometry Nodes with handcrafted elements

Figure 2. Manual and Geometry Nodes combined architectural forms in parametric modeling workflow

A key benefit of this approach is the dynamic linkage between the initial element and the final object’s components. Any alteration made to a source element is instantaneously reflected throughout the model via the interconnections established by the Geometry Nodes. Moreover, adjustable parameters have been incorporated to enable users to tailor the model to specific requirements. It is feasible to alter variables such as the number of curved stones above the bay, the number of vertical stones, as well as the overall width and height, including the number of oculi. Figure 3 demonstrates that altering a single parameter results in a proportional adjustment of the size and placement of each object to conform to the new desired configuration.

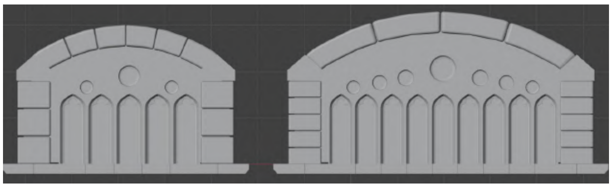


Figure 3. Variation of parametric architectural forms through numerical parameters adjustment

3.4 Integration of textures and procedural elements

In Blender, textures serve to enhance the realism of 3D model surfaces by adding intricate visual details that simulate material characteristics, such as roughness and reflectivity. These textures can be sourced from photographs or be computationally generated, allowing for extensive customization. Complementing this, procedural elements function as sophisticated algorithms that forge complex patterns and structures automatically. They facilitate the creation of scalable textures and dynamic shapes, enriching the visual diversity of scenes and providing creators with nuanced control over their designs without extensive manual modeling. Figure 4 depicts the texturing of the structures identified in figure 3. The texture is crafted by blending Voronoi and noise textures, enhanced with a color gradient for intricate details. This composite texture, incorporating color maps, normal maps, ambient occlusion, and displacement maps, adeptly mimics the nuances of stone materials such as contours, surface irregularities, and color variances. It achieves this while preserving a low-polygon initial geometry, optimizing graphical performance and yielding a model that is both lightweight and manageable. Although the same texture is applied to two objects, the procedural parameterization yields distinct outcomes for each, adding an additional layer of realism to the model.

Figure 4. Procedural texture application on parametric architectural models, demonstrating variation in surface detail and material realism

Figure 5. Birkenfels Castle rendered in Blender, showing its integration into a forest setting for virtual heritage reconstruction

4. RESULTS

4.1 Case study: Modeling of Birkenfels Castle

This case study focuses on Birkenfels Castle, located near Ottrott in Alsace, France. The aerial perspectives are shown in figures 1 and 6, which are both sourced from the website (Visitgrandest, 2024). Despite being partially in ruins, the castle's main structure remains intact. This scenario serves as a model to demonstrate the method of virtual reconstruction using a limited number of manually modeled elements.
Rhine castles are often characterized by the use of rusticated stones, which are finely cut along the edges for precise fitting, leaving the stone's core rough to save time and convey a sense of strength. These stones, with a central hole for lifting and positioning during construction, are essential for an accurate representation of these historical structures.

Figure 6. Front view of the Birkenfels Castle

To circumvent the unrealistic repetition effect, five models of stones with variable widths (ranging from 10 to 50 centimeters) were created, adhering to the aforementioned specifications. A remesh modifier was applied to ensure a correct topology for each stone. Additionally, a specific corner stone was designed for the junctions of the walls.
The use of Blender's Python API facilitated the random distribution of these stones along a curve that represents the castle's wall placement, with special attention to directional changes. The distance between each stone is precisely calculated to match the length of the walls. Users can set the total height of the wall with a floating-point value and define a range for the height of each layer of stone, adding a random and realistic appearance to the assembly. Consequently, each level is constructed with a variable height, ensuring that the total stack of layers exactly reaches the predetermined height for the castle walls.

Figure 7. 3D rendering of the Birkenfels Castle in a forest landscape, illustrating the integration of procedural modeling with natural environment in a virtual reconstruction

To accurately integrate our model within its actual geographical setting, we incorporated a Digital Terrain Model (DTM) derived from the high-definition LiDAR data provided by the National Institute of Geographic and Forest Information (IGN), referenced in the study at (IGN, 2024). The point cloud was initially processed and cleaned using CloudCompare (version 2.11.3). Afterward, the meshing was performed, and the "Instant Field-Aligned Meshes" algorithm introduced by Jakob et al. (2015) was employed for remeshing. Utilizing Blender's Geometry Nodes, we applied the instancing technique to distribute five different tree models throughout the DTM. This instancing approach allows for the multiplication of objects within the scene without increasing the overall triangle count, as each instance references back to a single mesh data block. By doing so, we could control the distribution density and introduce variations, such as random rotations, to enhance the natural appearance of the terrain. Instancing is particularly effective in maintaining performance, ensuring that the model's complexity does not compromise the rendering process despite the high number of trees. Figures 5 and 7 display the textured render of Birkenfels Castle, integrated into a DTM with a random instantiation of diverse tree species. The complexity of the scene is mitigated by the application of procedural textures and the instancing of objects, which together facilitate a scene that is both detailed and efficiently navigable.

4.2 Analysis of results: Flexibility and potential

The core advantage of this reconstruction approach is that every modified and duplicated object is based on a limited collection of manually modeled base objects. This ensures that the modeling time remains unchanged, irrespective of the castle's dimensions, location, or elevation. Additionally, by retaining connections to the original objects, any changes to a source element propagate to all linked duplicates. The parameterization of components is as follows:

- **Tiling:** Automated generation via Geometry Nodes. A curve profile drawn by the user is extruded and replicated to form a consistent roofing structure. Dynamic alterations of this curve profile enable adjustments based on archaeological findings specific to each castle's tile remnants. Figures 8 and 9 exemplify this concept, demonstrating that changing the entire tiling can be accomplished in just a few seconds.

Figure 8. A first tiling version

Figure 9. A second tiling version, automaticaly generated with Geometry Nodes

- **Brick Curtain Wall:** Automatically produced using a Geometry Nodes on a primitive block, conforming to the wall's overall dimensions. Geometry is scaled down, randomly distorted, and extruded to individualize bricks.

- **Roof Joints:** Created from a single manually modeled tile, instanced along a Bezier curve.

- **Castle Wall Stones:** Randomly generated from a handful of manually modeled stones, duplicated using a Python algorithm.

- **Vegetation Density:** The surrounding trees and grass density are modifiable through a parameter available to the user.

- **Windows:** Configured with Geometry Nodes to allow variations in size, scale, and stone count.

- **Substructure Rocks:** Produced with Geometry Nodes, applying noise to a simple shape defined by the user, dictating the rock's approximate dimensions.

- **Procedural Textures:** Enable random variation and the straightforward alteration of texture values, affecting color, normal map, ambient occlusion, and more.

- **Rendering:** Performed with Blender's "Cycles" rendering engine, leveraging ray-tracing for realistic results.

5. CONCLUSION

5.1 Summary of findings

To conclude, this paper presents a parametric modeling approach using the 3D modeling software Blender. By employing Python scripting, modifiers, and Geometry Nodes, parametric modeling is achieved with a small set of hand-modeled objects. Data can then be easily reused and modified, allowing for quick adaptation to various reconstruction scenarios for a single castle according to archaeologists' suggestions. Moreover, new objects modeled for each castle contribute to an expanding library of parametric objects, which can be used for modeling other Rhineland castles based on minimal on-site data acquisition.
Furthermore, Blender's capacity to process large datasets ensures that the 3D model manipulation remains straightforward and fluid. Properly applied textures simulate details and relief while maintaining the geometry as light as possible. In the final rendering phase, realistic images are produced using Blender's Cycles rendering engine, which is known for its advanced ray tracing capabilities that simulate the behavior of light for photorealistic imagery. Here, only images are showcased, but the methodology can be extended to video creation for public dissemination and promotion of historical sites.

5.2 Implications and future prospects

To propose this initial reconstruction, only a limited number of images sourced online were utilized to conceptualize a comprehensive view of the castle. Dimensions were approximated using Lidar data from IGN (2024). The next phase will involve on-site photogrammetric and laser scanning acquisitions to acquire precise measurements of the castle. Additionally, unique elements found on-site (such as coat

of arms, typical castle artifacts, engravings, etc.) could be beneficially scanned and directly integrated into the Blender project.
Furthermore, as Blender is not a real-time rendering engine, one of the prospective steps is to migrate the modeled and textured elements from Blender to Unreal Engine (Epic Games, 2024), which supports real-time visualization of large datasets. This transition is expected to enhance immersion significantly, but the compatibility of Geometry Nodes, modifiers, and textures between the software requires thorough investigation.

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