Managing 4D Modelling Supported by Modern Archaeology for the In-Depth Study of a Ruined Castle – Oedenbourg Castle in Alsace, France

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Abstract

The modelling work described in this paper begins with a review of the methodologies employed for data acquisition and modelling of the current state of the Oedenbourg Castle, Alsace, France. Preliminary topographical work was carried out to accurately georeference the site. An uav flight was organized to acquire aerial images. Photogrammetric processing supplemented by TLS measurements and uav images produce dense point clouds and meshed and textured models. Before the resumption of excavations in 2023, an initial sequence of 3D models has been produced, based on the most probable hypotheses to date. It included the following phases: 9^{th}-10th century, beginning of the 13^{th} century, late 13^{th} century. New excavations have enabled the archaeologist to complete or even propose new hypotheses with a different phasing, possibly calling into question certain previous models: 13^{th} century, before ¾ of the 13th century, last ¼ of 13th century, 14th, early 15th century. The paper will cover the detailed management, organization, and recovery of the various models in *Blender*, in particular with linked scenes to track their evolution over time as new knowledge is acquired and new hypotheses formulated. Among the fundamental steps involved in sustainable, scalable modelling, it is important to emphasize the following: positioning tools, elevation design, modelling/integration/placement of openings, scene render optimisation using Modifier, UV mapping and finally highlighting the evolution of modelling based on archaeological excavations with renderings of new 4D models and highlighting scientific knowledge.

1. Introduction

The Oedenbourg Castle (Figure 1) is located in Orschwiller (Bas-Rhin, France) a few hundred metres from the Haut-Koenigsbourg castle. Ruined, like most Alsatian castles, Oedenbourg has a Gothic dwelling and a main tower, a set of walls to the east, as well as a system of ditches on the western and eastern sides of the house.

Figure 1. Ruins of the dwelling of the Oedenbourg Castle.

During the Interreg VI – Châteaux rhénans – Burgen am Oberrhein project, INSA Strasbourg and Archaeology Alsace worked hand in hand to uncover theories of historical phasing of the Oedenburg site. Two hypotheses for the evolution of the castle have therefore been formulated. They are the result of an update of knowledge during the project that extends from 2023 to the end of 2025.

1.1 First Archaeological Hypothesis

The study of the Oedenbourg's ruins has been enriched by various archaeological research (building studies and excavations) over the past thirty years. It supplements very disparate and imprecise written sources. Indeed, before the middle of the 15th century, most written sources hardly distinguish the castles built on the Koenigsberg, the royal mountain. The toponym of Oedenbourg, which refers to an abandoned castle, appears for the first time in 1417. The most recent historical studies associate the site with the Rathsamhausen family, whose presence on the mountain has been attested since 1267. This date is relatively synchronous with the architectural style of the dwelling stylistically attributed to the third quarter of the 13th century.

Field research, which is very disparate, has been associated with scientific missions entrusted to various researchers (monumental study commissioned from the *Centre d'archéologie médiéval de Strasbourg* in 1990, excavations led by the University of Lodz in Poland in 1991-1993, etc.) or initiated as part of an encyclopaedic work on Alsatian castles (Biller and Metz, 1995). The most recent missions (1994 - 1995 and 2000) were associated with the consolidation of the remains, under the joint direction *of the Regional Archaeology Service* and the *Regional Conservation of Historic Monuments*. They made it possible to carry out a synthesis of knowledge, based both on the conclusions formulated previously and on new data acquired on the chronology of the dwelling and the adjoining shield wall. The conclusions of this work proposed a phasing distinguishing five periods, spread between the 10th and 15th centuries. The main tower and the house, separated by a small inner courtyard, are major elements of this site, dating from the 13th century.

A particular question focused on a monumental wall, barring the ridge to the east of the Gothic dwelling. The very crude appearance of the large masonry linked to the earth led one to believe that it was the remains of a fortification prior to the castle, attributed to the Carolingian (Erb, 1886) or Ottonian (Biller and Metz, 1995) periods, or even to the Gallic period (Ebhardt, 1902). A second hypothesis proposed to identify this wall with a false braie, built in the 15th century to defend the Gothic dwelling (Salch and Lerch, 1990). This delimited an orthogonal perimeter, extending the castle's footprint by about thirty meters to the east and protecting small buildings on one level. It was the acceptance of the first hypothesis that motivated the launch of a three-year excavation programme (2023-2025) during the Interreg VI project about Rhine Castles. The team's efforts were therefore focused on two sectors, the set of walls that delimit an eastern perimeter and the curtain wall that closes the "classical" castle to the west (Figure 2).

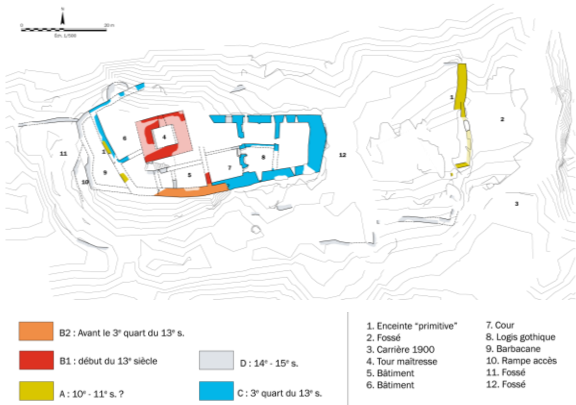

Figure 2. Chronological plan of the Oedenbourg site in 2022 (2023 pre-excavation) (Koch, 2024).

1.2 Updated Hypothesis after two Campaigns of Archaeological Excavations

The objective of the excavations was therefore to understand the function of the eastern fortified perimeter, to establish a more precise dating and to establish, or not, its synchrony with the western curtain wall. As the work progressed, it became apparent that the two sectors had different chronologies. The great technological distinction between the two constructions is linked to the use of lime mortar, identified in the west wall and totally absent from the eastern sector, particularly on the great wall. On this side, the documented masonry complex is very crude, evidence of limited investment in the construction programme, or even in response to an emergency requiring a reinforcement of the defences.

Figure 3. Chronological plan of the Oedenburg site in 2024 (after two archaeological excavation campaigns) (Koch, 2024).

The presence of a stone cannonball, shattered into three pieces to be used as rubble in the construction of a segment of wall, invalidates the "old" dating. Indeed, mechanical weapons such as the trebuchet did not exist before the beginning of the 13th century in our region, and a fortiori with powder in the case of a bombard, a weapon that appeared in the 15th century. Similarly, all these remains draw a more complex plan than the accepted assumptions, even in the case of a late fortification. De facto, the results of these excavations require a simplification of the chronology of the site (Figure 3). The "high" period was abandoned. In addition, no finds of furniture, in particular the guiding fossil that culinary ceramics may be for the archaeologist, indicate an occupation prior to the 13th century.

2. 4D Modelling Process

4D modelling is the main objective of the project. It is a question of digitally reconstructing the various archaeological evolutions of the site. These restorations are based on the archaeological hypotheses described above, but also on current topographical data. This project was then able to deal with many subjects such as field surveys, the creation of digital twins of the current state, the historical restitution in collaboration with Archaeology Alsace, the historical evaluation of the 4D restitutions or the enhancement of the castle (Koehl et al., 2024).

2.1 Topographic Surveys

In 2023, topographical surveys were carried out at Oedenbourg Castle, making it possible to digitise the current state (before the archaeological excavations in 2023) of the site. Mixed survey was carried out, combining photogrammetry and lasergrammetry. Indeed, a digitization campaign by TLS was carried out on the entire site, from the east ditch to the west ditch, outside, but also inside the ruin of the house. Similarly, several photographic uav campaigns have been carried out, mainly covering the built-up areas of Oedenbourg, as the vegetation cover was too great. These surveys were georeferenced thanks to a set of tacheometric and GNSS surveys.

2.2 Creation of Digital Twins based on Raw Data

Using all this data, a dense point cloud and then a textured mesh could be generated. These digital twins then made it possible to crystallize the state of the castle at a given moment (March-April 2023). These models were scaled and georeferenced in the national coordinate system (RGF93 - NGF-IGN69). This stage of the project consists of multiple processing, including photogrammetric, lasergrammetric and topographic. The digital twins obtained then form a working database. They are a metric, visual and morphological reference and will be used for the formulation of archaeological hypotheses and the modelling of previous historical phases of the castle.

2.3 4D Reconstructions

The 4D restitution of castles allows the visualisation of disappeared forms from the sites studied. We then speak of 4D to describe 3D models of the same object/site, mapped within a coherent time frame. 4D modelling then involves several interdisciplinary steps (Sommer, 2024).

2.3.1 Development of Working Assumptions: In a case such as Oedenbourg, the lack of written sources that would have described parts of the site, or iconographic sources reconstructing its components, refers the researcher to field data alone. Some parts of the reconstruction are based on the digital terrain model, which is easily accessible, as in the case of the dwelling preserved up to the level of the attic, while other parts that have disappeared are treated as a mere hypothesis. More systematic exchanges between archaeologists and computer graphics designers, at any stage of the model's creation, are therefore imperative. Finally, despite the establishment of primary conjectures at the beginning of the project, the development of archaeological hypotheses is closely linked to 3D modelling. The archaeologist's thinking is bound to evolve with the creation of the model and this exercise makes it possible to validate or invalidate hypotheses as they are designed in 3D.

2.3.2 3D Modelling: The 3D modelling stage consists of transcribing the archaeological hypotheses digitally in 3D. In 2023, the modelling was processed using *Autodesk Maya*. Then, the project involving several castles, which were modelled in *Blender*, the entire rest of the restitution process was carried out in *Blender*. This software has many advantages such as its free aspect, its library of tools and its very active community facilitating problem solving and generating many additional tools.
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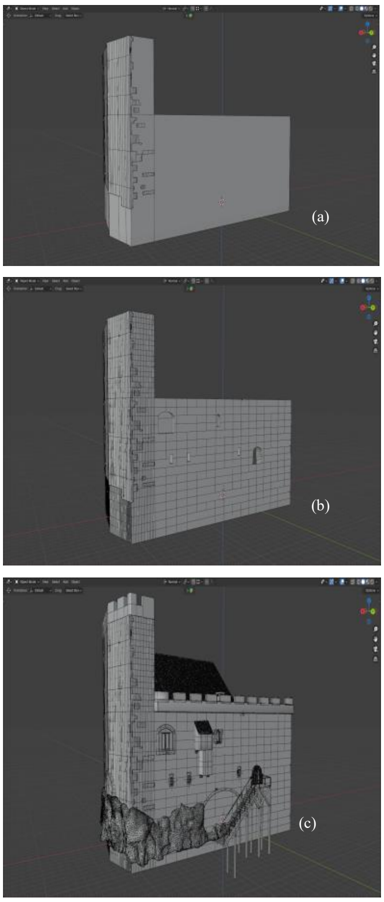

Figure 4. Modelling process of the dwelling of the Oedenbourg Castle (13th century): (a) walls - (b) openings - (c) details and layout around the main frame.

3D modelling begins with modelling walls using blueprints. The methodology consists of starting in 2D with the modelling of the wall's footprint using a plan, then extruding with height knowledge. This step generates a model with a primary level of detail. The openings (door, windows, bays, etc.) are then added, and the details such as gutters, latrines and roofs are created in a second step (Figure 4).

The project is carried out in a scientific context, combining archaeology and topography. The models are therefore carried out at full scale and in a known coordinate system. These are partly based on metric topographic data (point clouds, meshes, plans, orthophotographs) obtained by the processes described in a previous part. With *Blender*, the mesh in .obj format was mainly used. The mesh was decimated into triangles and shifted to coordinates to streamline the manipulations within the software (Figure 5).

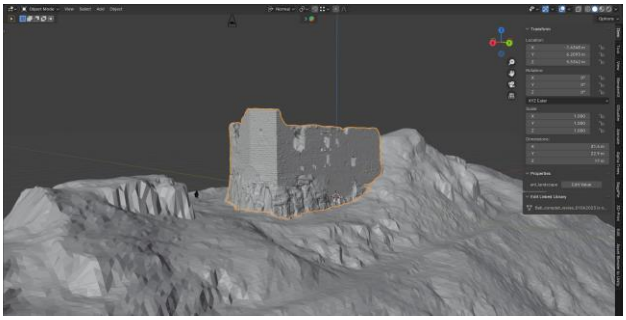

Figure 5. Blender scene composed of the mesh of Oedenbourg's ruins, georeferenced in RGF93 - NGF-IGN69, negatively shifted to 0, 0, 0 coordinates.

Modelling based on the mesh allows us to have a reference in terms of position, dimension, morphology and aesthetics. We can give the example of the south ribbed bays of the house (Figure 6), whose arches and part of the jamb are still preserved. The mesh can then be used as a reference in terms of dimensions but also position. In addition, almost all the positions of the openings can be interpreted thanks to the mesh, as well as for the doors and chimneys.

Figure 6. South pointed windows of the 13th century dwelling of Oedenbourg Castle.

The corbelled latrines on the north façade (Figure 7) are also a good example. Indeed, the consoles on which they rested allow us to position them. It is even possible to distinguish the height of the roof thanks to the brackets on which the roof rested, but also the drip mouldings that protected the roof from rainwater runoff.

Another method for accurately modelling is based on reference images imported into *Blender* (Figure 8). This method is widely

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used for modelling ground footprint, architectural elements or to deduce the elevations of objects. The images concerned can be plans, technical architectural drawings (Figure 9) or orthophotographs. We prioritize these types of data for their accuracy as well as their orthographic representation.

Figure 7. Remains of the corbelled latrines on the north façade.

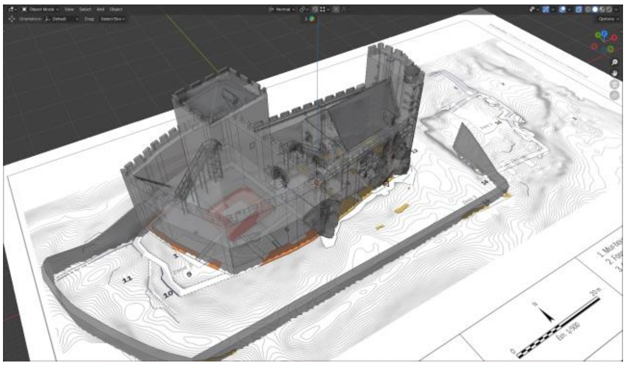

Figure 8. Modelling of the walls in *Blender* from a topographic plan of the Oedenbourg (on plan by (Koch, 2024)).

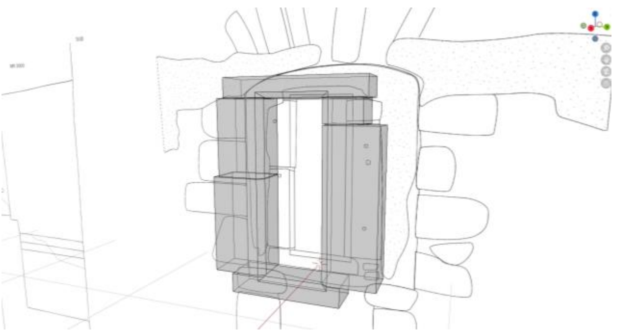

Figure 9. Modelling an archer in *Blender* from a survey plan (Koch, 2022).

2.3.3 Archeological Evaluation of the 4D Model: From a scientific point of view, the work evaluation process is fundamental. First, we can mention the centimetric accuracy of the restitutions (positioning and dimensions) depending on three aspects: the accuracy of the topographic surveys, the accuracy of the processing of the raw data and the pointing/positioning error of the restitutions on the field data during 3D modelling. In the case of the project, a tolerance on the restitutions, more or less important, may be retained (up to 10 cm), the objective of the project being mainly visualization. Concerning the field data and their processing, topographic precision (less than 5 cm) is applied, guaranteeing the accuracy and therefore reliability of the resulting data.

In addition, an archaeological assessment is essential. It is a question of setting a degree of uncertainty (Landes et al., 2019) on each object or group of objects placed by the archaeologist. The assessment is then possible thanks to a colour scale.
The assessment may first be sketchy. It is visually defined by three colours. Evaluation is in fact a classification of restitution elements according to three categories:
- The element was found on the site; it is then colored green.
- The element comes from hypotheses and analogies drawn from archaeological analyses / excavations. The element is then colored yellow.
- The element is the result of mere speculation; it is coloured red.

This draft assessment is actually very general. It includes criteria such as the position, shape or size of the element. However, it provides a result that is easily interpretable according to the criteria of restitution of evolutions and virtual restitution of Stefani (2010).

In order to go further in the analysis of restitutions, a second evaluation method is proposed (Koehl et al., 2024). It is based on two methods described by Hermon et al. (2006) and Landes et al. (2019):
Landes et al. (2019) propose a LoU (uncertainty) scale adapted to the historical restitution of poorly documented archaeological sites. This scale is accompanied by a colorimetric visual representation of uncertainty.
Hermon et al. (2006) introduce a more structured method. Based on two indices (uncertainty and importance), the object is evaluated according to several criteria such as dimensions, position, texture, etc. This method allows a kind of weighting of the uncertainty of restitution according to the importance of the object from an archaeological point of view
Our evaluation is presented in the form of a table (Table 1) exposing on the one hand the element judged, and on the other the criteria to be judged by the archaeologist according to the two criteria proposed by Hermon et al. (2006):

The uncertainty ranges from 0 to 1 and is divided into four intervals assigned to the LoU scale defined by Landes et al., (2019):
LoU 1: {0.8;0.9;1}: Very reliable, demonstrated by analyses and archaeological excavations.
LoU 2: {0.5;0.6; 0.7}: Reliable, the element is partially existent and can be deduced by geometry.
LoU 3: {0.2;0.3;0.4}: Unreliable, the element no longer exists and deduced by analogy to other elements or sites.
LoU 4: {0;0.1}: Unreliable, the element is a pure hypothesis.

Importance ranges from 0 to 1 (Hermon et al., 2006):
{0.8; 0.9;1}: Very important
{0.5; 0.6;0.7} : Important
{0.2;0.3;0.4}: Not Important
{0;0.1} : Non important

Finally, we obtain the final evaluation criteria, R_n the individual evaluation criterion (per object) and R the general evaluation criterion (per set of objects) according to the method of Hermon et al. (2006) (always between 0 and 1). We associate them with a colour scale such as: {0.8;0.9;1} in green, {0.5;0.6;0.7} in orange, {0.2,0.3;0.4} in yellow; {0;0.1} in red.

Historical phase	Evaluation categrory		Existence	Dimensions	Position	Material	rn	in	Rn
A	East surrounding	Uncertainty	1.0	1.0	1.0	1.0	1.00	1.00	**1.00**
		Importance	1.0	1.0	1.0	1.0			
	North surrounding	Uncertainty	0.4	0.4	0.4	0.4	0.40	0.70	**0.36**
		Importance	0.7	0.7	0.7	0.7			
								R	**0.68**

Table 1. Example of an archaeological evaluation table based on (Landes et al., 2019) and (Hermon et al., 2006)

Note: The choice of evaluation criteria (existence, shape, dimensions, position, materials) was made by modelling experience. Indeed, it is these criteria on which the reflections have taken place and which may have involved difficulties.

2.4 Enhancement of the 4D Reconstructions

White 3D models are already very telling, allowing user to interpret the position of elements, their relative sizes, as well as their appearance. However, this mode of visualization is not common. And not everyone masters 3D manipulation. As part of the project, several deliverables have therefore been developed. Models can be textured in two main ways: texturing based on images or using procedural materials.

Texturing with images requires special attention to the images used and the UV maps. Indeed, for a realistic rendering, the images must be seamless. In addition, in the case of working with texture atlases, the UV maps must be adapted and worked on beforehand.

Procedural texturing allows for greater freedom. It promotes material customization, simplifies material application, and provides realistic visual consistency. The parametric aspect is very important in the collaborative approach, as it allows for controlled modification of the material.

The castle models are then cartographically designed. A 3D model of the terrain is created. It can be derived from reality (HD LiDAR in France (IGN, 2025)), field surveys or free models (OpenStreetMap, 2025). In all cases, they are reworked in order to adapt to the historical hypotheses of the place. It can be noted that the data provided by the HD LiDAR make it possible to locate the ancient medieval paths preserved to the present day (Figure 10).

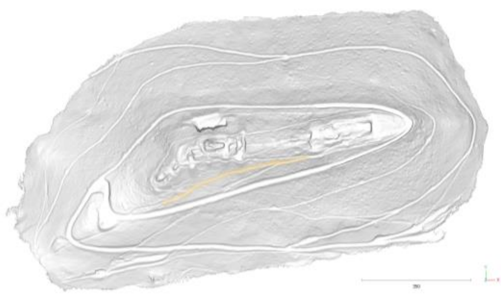

Figure 10. HD LiDAR of the area around Oedenbourg (in yellow: preserved medieval path).

The terrain is then covered with vegetation. Weather conditions can also be added to the scene, making it all the livelier. At this stage, the 3D model can still only be viewed in *Blender*. One of the most effective methods of enhancement is image or video rendering. Based on camera positions within *Blender*, rendering allows the production of standard audiovisual content, or in virtual reality with panoramic images / videos that can be implemented within a VR system. Video games can also be created, requiring an additional step of adapting the models. Another way to promote 4D models is through 3D printing. The models can be individual to each historical phase of the castle or presented as an evolving puzzle. The latter makes it possible to recreate the history (particularly architectural) of the castle by adding and removing the building elements when they evolve over time.

3. Updating Models and Workflows

In the case of the project, the notion of 4D takes on its full meaning, and in the first sense, we will speak of 4D to describe the architectural evolution of the castle over the centuries. Then, we can talk about 4D concerning the evolution of archaeological and historical knowledge about the castle over the decades. And finally, we will talk about 4D to describe the evolution of modelling through working methods. Indeed, the learning and experience acquired through this interdisciplinary collaboration allows a refinement of the methodology adopted for 3D modelling in a context of castle restitution.

3.1 Invalidate Working Assumptions by Archaeological Excavations

From the beginning of the excavation, a discrepancy appeared between the progress of the modelling, which reconstructs several supposed periods, and the reality of the periods observed. In view of the evolution of knowledge, the primitive phase became obsolete and the model had to be readapted. However, it is still interesting for this exercise to keep this model for educational purposes. However, it will be necessary to clearly specify its status as a supposition, not a restitution, of a historical hypothesis for the public. To avoid any confusion, the status of this document should remain relatively confidential, to make room for restitutions based on field research.

3.2 Model Corrections and Implementation of new Working Methods

The correction of models takes place throughout the 4D rendering process, whether they are adjustments or major corrections following changes to an archaeological hypothesis. Through the interdisciplinary collaboration for the creation of 4D models of Oedenbourg Castle, many technical aspects of the modelling have been improved. These improvements are intended to facilitate the modification of 3D models, to optimize the size of the scene, but also the management of the different sets of objects, particularly concerning temporality or to secure the scenes during modification. First, the use of *modifier* (Sommer, 2024) gives a non-destructive aspect to the modelling process.

The most commonly used *modifiers* are:
Booleans, for the creation of holes (for windows and doors in particular), *Array* that creates off-staggered copies of the object according to the chosen parameters, *Curve*, which allows user to unforce a mesh object in a curve, *Subdivision surface*, which, as its name suggests, divides the faces of a mesh object

Secondly, the organization of the objects of the same *Blender* scene is also improved through the management of the *Outliner* (tree structure presenting the objects of the scene). This organization is achieved through *collection creation,* as well as through *parent-child relationships* between related objects. Indeed, parenting allows user to attach several objects in order to facilitate the editing of their transformation parameters. In addition, it allows for the organization of the *Outliner*. Finally, the *Link* function has been added to the workflow in order to improve the organization and security of the models in a very effective way. Indeed, it allows a segmentation of large sets of objects in different *Blender* scenes, thus optimizing the organization in the *Outliner* of the link block's home stage, but also the security of the different data blocks since a link block is not editable in the home scene. This process therefore creates a set of interlocking scenes. To illustrate these improvements, the example of the door frame of the north entrance to the Oedenbourg’s dwelling (end of the 13th century) is given. The dimensions and appearance of the exterior door frame (jamb and vault) are preserved and visible on the grounds. The external frame was modelled manually, respecting the dimensions and the general appearance of the sandstone blocks (bossed or not). To model this door frame in *Blender*, two cubes and a curve are created. Then, thanks to the *modifiers* (*Array*, *Subdivision Surface*, *Displace*, *Curve*), the door frame is generated. A lighter, non-destructive stage was obtained in this way. The door frame scene was then *linked* in the general scene of the castle's restitution (Figure 11). Note that textures are also *Link*.

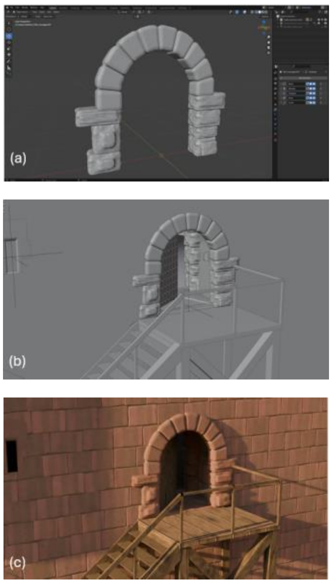

Figure 11. Non-destructive modelling of the North door frame: (a) *Blender* stage of the door frame; (b) white model of the castle (late 13th century) with the Link door frame; (c) textured rendering with the Link door frame.

3.3 4D Rendering

The 4D can be viewed through a succession of images of the castle at different times, or through a video depicting the evolution of the castle. This type of rendering is aesthetic and allows the public to understand the temporality of the castle.
In another context, rendering also makes it possible to highlight the degree of uncertainty of the restitutions made throughout the project. This approach allows to put into perspective the evolution of archaeological knowledge over the three years of the project.

All final renderings are made in *Blender* using the *Cycles* renderer.

4. Results

4.1 Visual Results

The first results are visual, with image and video renderings of the different historical stages of the castle for both versions of hypotheses. The first renderings were made in 2023 in *Lumion* (2023) (Figure 12). Indeed, at this period of the project, tests under several rendering software were carried out. *Lumion* was selected for its completeness and user-friendliness.

In a second phase, in 2024-2025, the models of the Oedenbourg Castle were transferred to *Blender*. The correction following the evolution of archaeological knowledge, the texturing and the renderings were therefore processed in *Blender* (Figure 13).

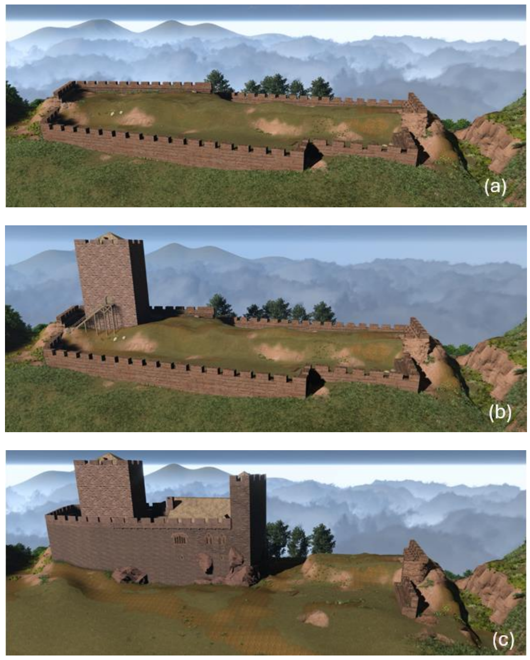

Figure 12. 4D modelling of Oedenbourg Castle based on 2023 assumptions. (a) 10th-11th century; (b) early 13th century; (c) end of the 13th century. Modelled with *Autodesk Maya* and rendered with *Lumion*.

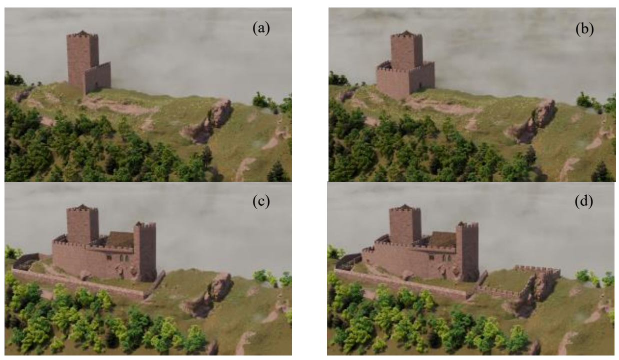

Figure 13. 4D modelling of Oedenbourg Castle based on 2024/2025 assumptions. (a) early 13th century; (b) before the 3rd quarter of the 13th century; (c) last third of the 13th century; (d) late 14th-15th century. Corrections and renderings made with *Blender*.

4.2 Evaluation of the Models

4.2.1. Evaluation of the 2023 Modelling: In the first phase of modelling (based on pre-excavation data, i.e. pre-2023), we carried out the two types of assessment described above (summary and complex) (Figure 14 and Figure 15). Concerning the two assessments, we note that the further back in time we go, the greater the uncertainty, which is consistent with the archaeological approach and with the ruined remains on the ground. Indeed, historical and archaeological research has focused on the house, the most substantial and best- preserved part of the castle. In addition, many elements of phase A and phase B have disappeared or are not accessible. The hypotheses are therefore necessarily stronger for phase C.

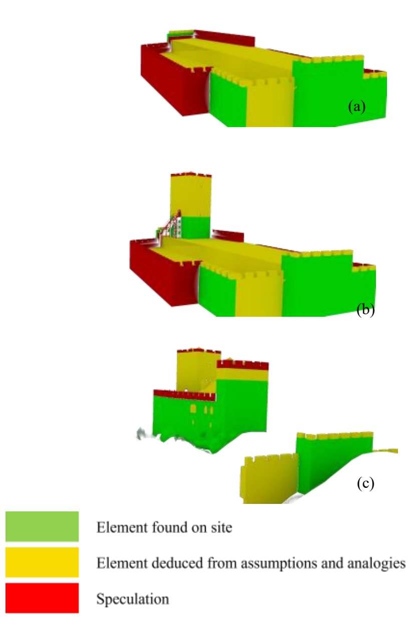

Figure 14. Colorimetric representation of the summary evaluation of the three temporal phases of the Oedenbourg site in 2023; (a) 10th-11th century; (b) early 13th century; (c) end of the 13th century

Regarding the evaluation by criteria (Landes et al., 2019 and Hermon et al. 2006), we obtain R coefficients equal to 0.3 for phase A, 0.7 for phase B and 0.9 for phase C, which validates our previous analysis

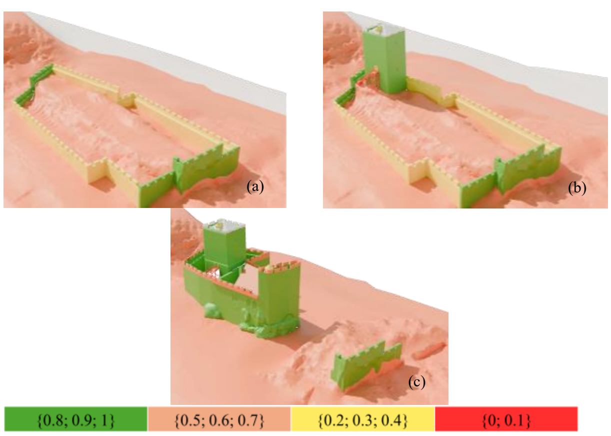

Figure 15. Colorimetric representation of the criteria evaluation in 2023. (a) of the 10th-11th century; (b) early 13th century; (c) end of the 13th century.

4.2.2 Evaluation of the 2025 Modelling: Following the updating of the archaeological hypotheses, a new archaeological assessment is necessary. We conduct the evaluation by criteria only (Figure 16). For the complex evaluation, we notice a rather high R criterion (0.76) on phases A2 and B, which are quite close in time. The last phase, which is an extension of phase B, is evaluated with a lower R (0.67) due to the large number of development elements evaluated. These elements are a fortiori less certain, because they are more futile and therefore less known. The first phase is much less certain with an R equal to 0.50. Indeed, despite fairly certain and important elements such as the tower, elements such as the wooden entrance staircase or the latrines are considered uncertain and unimportant, lowering the scores.

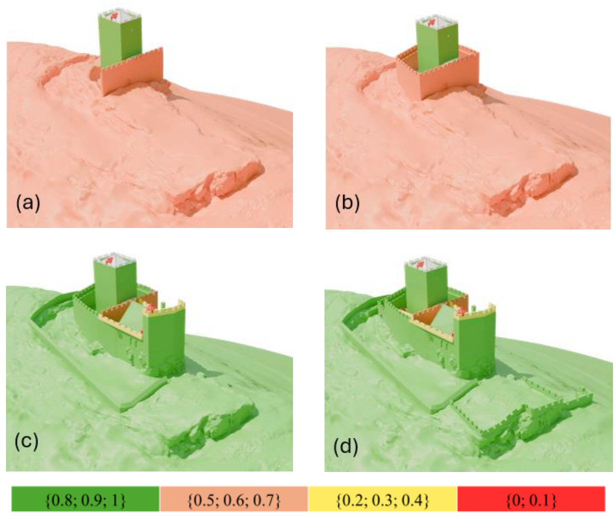

Figure 16. Colorimetric representation of the criteria assessment in 2025 (based on the methods of Landes et al. (2019) and Hermon et al. (2006). Representation of Phase A1 (a), A2 (b), B (c) and C (d) Criterion R_n

4.2.3 Cross-referencing of Assessments (2023 – 2025): The analysis of the evolution of assessments before and after the update of archaeological knowledge is all the more interesting. These analyses can only be carried out on the elements common to the two sets of modelling but can also relate to the discoveries made on site during the excavations.

For example, we had assessed the west and east enclosures of Phase A in 2023 as important and more or less certain. These estimates are still valid in 2025 for phases A1 and A2 and are reinforced thanks to archaeological excavations. The same goes for the main tower. The main differences are related to the addition of elements following archaeological discoveries during excavations.

We note that some assumptions for 2023 have been completely modified in 2025, such as the north enclosure of 2023, which disappeared in 2025, or the southern enclosure, which has changed its morphology and even its function.

Finally, it is quite difficult to compare our two assessments. Sometimes the hypotheses have been refuted, other times, certain elements have changed eras. However, we can still note that for imposing elements such as the tower, the dwelling or parts of the enclosure, the uncertainties remain more or less the same.

5. Conclusion

The aim of 4D modelling of castles is to transcribe the life of the latter over time (3D + 4D). This is a vast subject, sensitive to change. Here, this notion of 4D is all the more interesting because of the ambivalence of our case. Started in 2023 and with the associated archaeological discoveries, the work has brought to light two versions of the history of the Oedenbourg Castle. This ambivalence is then reflected in the 3D modelling of the different historical phases of the castle, but also in the evolution of these models with scientific progress. This double notion of 4D is very interesting, because it makes it possible to freeze the state of knowledge at a given moment and constitutes a library of digital data.

The *Blender* tools used during 4D modelling were then described. The organization and construction of these models were explained, with the aim of facilitating transmission and updating. In fact, the evolution could continue with the last year of archaeological excavations to come.

Whereas graphical representations, plans, and 3D perspectives once played the role of illustrations of knowledge supported by written reports, 4D modelling is now an integral part of the process of reflection and acquisition of new knowledge. They enable us to confront hypotheses, verify technical aspects, highlight functional incompatibilities, and simulate or concretize hypotheses. For this reason, modelling as part of a scientific process is becoming more than evolutionary, in the form of a simulation tool that must move towards interactive rendering. The complexity of modelling does not yet allow this real-time interaction, but thoughtful structuring of the model, appropriate parameterization, and optimal use of integrated mechanisms such as *Modifier*, *Geometry Nodes,* or *Shader Nodes* tend to lead to this increased interactivity.

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