

ON STAGE IN ANTIQUITY, ON SCREEN IN THE DIGITAL AGE: TWO THOUSAND YEARS OF URBAN PRESENCE AND INTEGRATION OF THE THEATRE IN PRIENE

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ABSTRACT

The theatre of Priene, among the best-preserved in Asia Minor, represents an exemplary case study for testing integrated methods of digital surveying, procedural modelling, and virtual reality applied to archaeology. The work begins with the documentation of Wiegand and Schrader and with Armin von Gerkan's hypotheses, adopted as the reference for reconstructing the stage and compared with a photogrammetric survey carried out through ground and drone imagery. The model was decomposed into typological parts and organized through objects and instances described by XML metadata interoperable across Rhinoceros, Blender, and Unity. Post-production introduced sculpting, procedural materials, and morphological variants, placing the final result within an explorable VR environment. The final model explicitly distinguishes between the existing state, confirmed reconstruction, and hypothesis, restoring clarity to a fragmented monument and offering an operational tool for research, education, and dissemination.

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Ancient Priene and its theatre

Priene was founded in the Caria region of the western part of Anatolia, the present Turkey, the settlement is situated on the southern slope of Mount Mycale, overlooking what in antiquity was a gulf opening into the Aegean Sea. From the Archaic period to the Hellenistic age, however, the silting of the Maeander River, once entering the sea at the East of Priene, had gradually pushed the coastline westward, detaching Priene from the seashore that had once defined its economy and strategic importance. The city was architecturally realised in the IV century BCE, providing a model environment for the implementation of a rational, orthogonal urban plan, organized in a series of large terraces. The sloppy topography imposed constraints that required a specific architectural attention, producing one of the clearest surviving examples of Hellenistic city planning. Priene is a paradigmatic example of urban planning of that time (Wycherley, 1945). Its street grid, in which it is possible to recognize the Hippodamian principles (Castagnoli, 1956), organises the city into regular sectors aligned to the cardinal directions, though subtly adapted to the mountain slope. Public buildings at Priene, including the Agora, the *Bouleuterion*, the *Prytaneion*, and the Theatre, participate in a coherent architectural vocabulary, presenting specific solutions, but remaining coherent to the main city layout.

Figure 1. View of the theatre, July 2022. View of the archaeological site of the theatre. Panorama taken during the photographic survey phase.

The Theatre of Priene is situated on the third urban terrace of the ancient city, in an intermediate position between the Agora and the Sanctuary of Athena Polias (Fig. 1). The building exploits the terrain and cliff slope and has most of the additional parts and all the external elements constructed in marble blocks. It exhibits the canonical articulation of Greek theatres (Lawrence, Tomlinson, 1996): *cavea*, *proedria*, *orchestra*, *proskenion*, stage building, and *parodoi*. The *cavea* is organized into five radial sectors, separated by six stairways approximately 0.92–0.96 metres wide (about two cubits, *pechys*) (Cardarelli, 2003). The lower rows are carved directly into the rock, while the upper rows rest on an artificial foundation made of regular stone blocks; only part of these upper rows survives today, while many of the benches have been lost. The seats consist of superimposed slabs with an average height between 0.39 and 0.40 metres, calibrated to the natural slope of the hillside (a little less than one cubit, *pechys*).

The curved layout of the benches, re-constructible thanks to historical surveys and comparison with photogrammetry, shows slight irregularities suggesting the use of arcs with non-coincident centres. This aspect, apparently secondary, becomes relevant in digital modelling because it requires avoiding geometric simplifications that are too rigid and would misrepresent the original construction logic.

Between the *cavea* and the *orchestra* lies the *proedria*, arranged as a paved band of stone blocks that hosted the row of honorary seats. In this area, five marble thrones and a central altar are still preserved, elements likely added during a later phase compared to the original configuration. The thrones feature articulated bases, lion-paw legs, vegetal motifs recalling a creeper ivy, and curved backs with Ionic-volute armrests; the quality of the carving and attention to detail confirm the representative function of this zone, reserved for civic and religious authorities.

The *orchestra* measures 18.65 metres (about 46.5 cubits, *pechys*) in diameter and corresponds almost exactly to the length of the *proskenion*. The latter represents one of the distinguishing features of the Theatre of Priene, as it preserves twelve frontal pillars and several lateral ones still standing. The Doric entablature, now fragmentary, originally displayed rich polychromies: triglyphs outlined in purple, metopes alternating in black and white, red cornices and fillets, blue architraves. These painted traces, documented by Wiegand and Schrader (Wiegand, Schrader, 1895-1898), were adopted as references for defining materials in the digital reconstruction.

From the *proskenion* façade, stone beams project toward the rear, connecting the scene front to the back wall and supporting the wooden floor of the upper level. The stage rooms, now completely lost, were accessible through five doors whose positions are re-constructible thanks to historical drawings. The stage building, particularly its vertical development and its relationship with the *proskenion*, was reconstructed following the hypothesis proposed by Armin Von Gerkan, which integrates the Priene data with typological comparisons to other theatres (Gerkan, 1921). The *parodoi*, located on the sides of the scene, still preserve their masonry access structures and constitute a useful reference and an additional point of comparison between the existing state and the reconstruction.

The Theatre of Priene offers a significant amount of preserved lower architectural elements and is well described by high-quality historical documentation. This dual condition makes it possible to produce a digital reconstruction that does not merely offer a formal restitution but explicitly clarifies the relationship between what is preserved, what can be reconstructed with reasonable certainty, and what can be brought to visualization only using very hypothetical ideas about its original state.

The Photogrammetric Survey

The definition of a digital model describing the current state was carried out through a photogrammetric survey that combined ground-based and drone-based imagery. A total of 824 images were acquired: 795 ground shots taken with a SONY ILCE-6000 mirrorless camera offering an APS-C sensor with 24 Mp resolution, equipped with a Sony E 16-50 mm f/3.5-5.6 lens and, for the detailed recording of the *proedria*, with a Nikon D800e, with a full-frame sensor at 47.3 Mp resolution, equipped with a Micro Nikkor 60mm F2.8 macro lens; and 29 aerial images, produced using a DJI Spark drone, with a 12 Mp sensor, flying at low altitude above the *orchestra* and the *cavea*. The contribution of the drone shots, even if limited to just 29 images (because of some technical issues happened during the survey operations), was a significant integration in terms of scaling and georeferencing the final model thanks to the integrated GPS data in each shot. The ground shots followed a radial path along the *cavea* and a linear path along the *proskenion*, with multiple fan-shaped captures to ensure redundant coverage of areas otherwise at risk of producing occlusion spaces.

The Structure from Motion Image Matching photogrammetry (SfM/IM) processing was performed in EG RealityCapture release 1.5, which combines fast processing, quality results

Figure 2. Plan view from the SfM/IM photogrammetry, final restitution of the photogrammetric model of the existing state exported from RealityCapture after the alignment of all components (drone and ground photos) through control points.

and practical early post processing of the produced meshes, texturing and direct orthophotos production. The initial alignment of the images generated several separate components due to the presence of vegetation (an element that tends to change position with a minimal breeze and so impede a correct matching of the pictures), visual discontinuities, and significant pixel-size differences between aerial and terrestrial shots. To bring the model into a single referenced system, a wide set of corresponding Control Points were identified across the various components, placed on clearly recognizable elements (slab edges, throne bases, joint intersections). Introducing at least three (but mostly six) homologous points between each component made it possible to automatically re-process the SfM/IM alignment with a full merging of all the components into a single model (Fig. 2). After the completion of this correct alignment the resulting point cloud was used for producing the polygonal model, then textured and simplified for multimedia uses. A simplified version made of



just 800.000 triangles was then uploaded to the Sketchfab.com platform, for easy sharing of this first digital version of the theatre. This model can be visualized (and downloaded) at the following link: <https://skfb.ly/oDNEG>. This online model also contains the direct links for visualizing the single thrones, which had a specific photogrammetric campaign and processing, so to have them available as single specific models as well.

Digital Modelling

The goal of the digital modelling process was not to produce a single static model, but to construct an information structure capable of explicitly describe the geometric and typological functioning of the theatre. To this end, the work was carried out in McNeel Rhinoceros 3D release 7 with the support of the Grasshopper plug-in, organizing the complexity of the monument into a network of objects, instances, and metadata. This process is a step forward from the direct automatic modelling produced by the SfM/IM photogrammetry, which moves to be the base for a complete remodelling that is more similar to a real constructive process than to an automatic digitalization.

Deconstruction and macro-structure

The theatre was divided into six macro-groups: *cavea*, *proedria*, *orchestra*, *proskenion* and stage building, and *parodoi*. Each group includes sets of recurring elements: steps, benches, bases, backs, thrones, columns, pillars, beams, slabs. For each typology, a single reference object was modelled, conceived as a simple geometric “prototype”. The repetition of elements within the theatre occurs exclusively through instances, generated and controlled parametrically (Fig. 3).



Figure 3. Digital reconstruction of the theatre, final phase of the modelling process in Blender, after importing the construction details through metadata via a Python script. The resulting model was obtained by refining the construction details through sculpting and texturing using OpenShadingLanguage.

This choice makes it possible to drastically reduce the computational weight of the model, simplify updates, and make the relationship between typology and occurrence explicit. Any modification to the reference object automatically propagates to all its instances, maintaining the overall coherence of the system.

Generative elements

Generative elements are abstract geometries that define the spatial arrangement of the components. Linear elements rely on points and vectors, curved ones on oriented curves, and complex joints on reference planes or surfaces. The curves were extracted from the photogrammetric model by projecting the outlines of the *cavea*, the *proedria*, and the *proskenion* onto plan view and removing local irregularities.

These curves were parametrized within the 0–1 interval, assigning each parametric value a point in space and a local reference system (a triad of axes). On these planes, the transformations required to place the instances, translation, rotation, and, where necessary, slight scaling, were calculated. This ensures that the repetition of seats or *proskenion* blocks follows the real curvature of the theatre, including small deviations from an ideal geometry.

In areas where the original blocks are no longer present, particularly in the upper part of the *cavea*, the arrangement was reconstructed by interpolating the available data: the average distance between slabs, the apparent radius of preserved sectors, and the alignment with the retaining walls. The geometric assumptions adopted were explicitly marked in later stages through metadata categorization (Rosone, Verdiani, 2024).

The resulting mesh was densified and subsequently simplified, maintaining high definition in key areas (*proedria*, *proskenion*, *orchestra*) and reducing detail in peripheral zones. A set of high-resolution textures preserved the chromatic and material information necessary for the reconstruction phase. Metric verification was carried out by comparing the model with the measurements recorded by Wiegand and Schrader: the deviations observed fall within an acceptable margin for an indirect survey, making the model suitable for the subsequent phase of procedural modelling.

Objects, instances, and deformations

The objects were modelled in Rhinoceros as low complexity meshes, sufficient to clearly describe the basic form of each element. The instances are generated in Grasshopper, which calculates for each one the full set of transformations

derived from the generative elements. This procedure produced thousands of components with complete control over their positioning.

For curved elements or those adapted to non-planar surfaces, such as the backs of the *proedria* or certain slabs of the *cavea*, the process continued in Blender using CurveDeform and similar modifiers. In practice, the linear object is “wrapped” along a reference curve while maintaining consistent proportions and detail. Here as well, the deformation is described within the metadata, ensuring that the relationship between object, curve, and instance remains fully traceable.

XML metadata

The informational structure of the model is defined through a metadata system exported in eXtensible Markup Language, XML format (Erik T. Ray, 2001). Each object and each instance correspond to a node within the XML tree and is described through:

- the name of the typological object;
- the path to the reference mesh file;
- any associated generative curve or surface;
- position, rotation, and scale coordinates;
- the assigned morphological variant;
- the reliability category (existing state, confirmed reconstruction, hypothesis).

This structure allows the model to be reloaded and regenerated across different environments without loss of information. The XML file therefore does not simply list objects: it describes the procedural logic that determined their spatial arrangement, enabling the entire process to be reconstructed directly from the data (Fig. 4).

Verification and classification

Once the procedural model was generated, it was imported back into McNeel Rhinoceros 3D and overlaid onto the photogrammetric mesh. Verification concerned both geometric coherence and the relationships between parts (alignments, symmetries, distances between key elements). To express the degree of reliability across different portions, a chromatic classification system was adopted: green for elements matching the surveyed existing state; yellow for parts reconstructed with strong support from historical sources; red for hypothetical elements, especially in the upper portions of the stage and the higher levels of the *proskenion* (Fig. 5).

This visual distinction, combined with the categories stored within the metadata, allows anyone using the model to im-

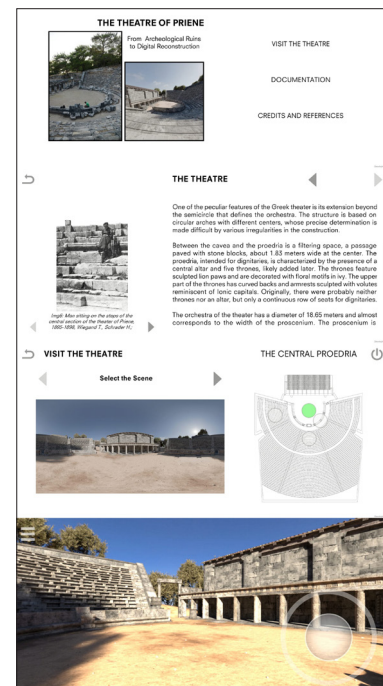
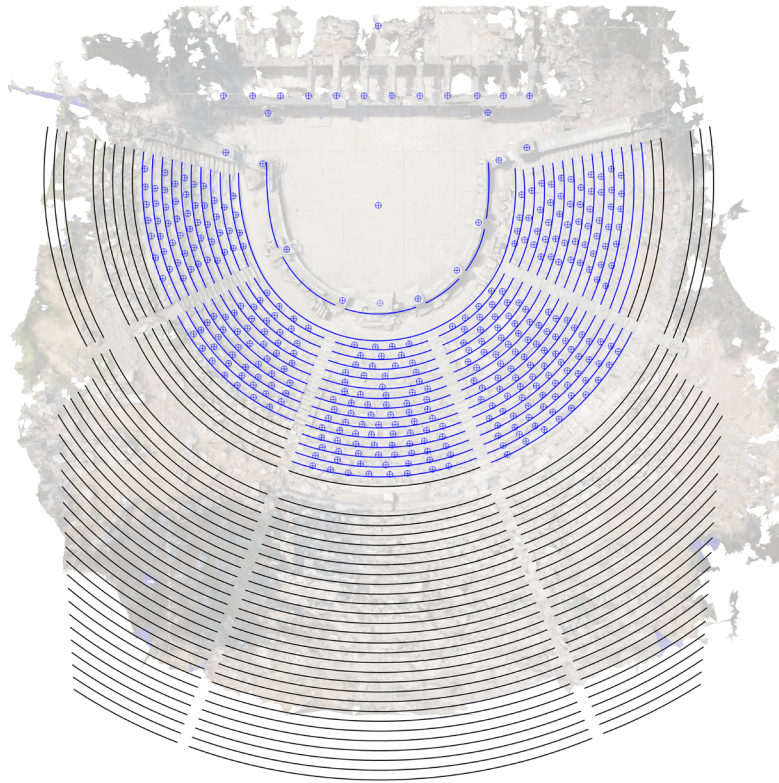


Figure 4. The APP for the virtual visit, screenshot from the 3D and contents. Through the app, created with Unity, it was possible to select viewpoints exported from the final model as HDRI panoramas for the exploration of the reconstructed site according to the archaeological hypotheses.

Figure 5. Generative modelling and optimization; through the generative elements it was possible to define procedural generation patterns adapted to the shape of the existing state. Each constructed detail is aligned and oriented through transformation criteria that define its position, including hypothetical ones where the element is no longer present in the current configuration.



mediately recognize the nature of each element, avoiding the misconception of a unified reconstruction when in reality it is based on very different levels of certainty.

Digital Rendering and Photorealism

The transition from procedural modelling to graphical rendering took place using Blender from Blender Foundation, a good, well diffused and functional freeware software for digital 3D modelling, still image and video creation with full features for texturing, model optimization and quality graphic generation. The model was imported in Blender with its XML metadata. The goal was not merely to obtain a convincing image, but to construct a consistent scene with a robust characterization aimed to help the perception of the historical period defined for the reconstruction, in the specific case, the one corresponding to the Doric phase documented by Wiegand, Schrader, and Gerkan, while excluding later additions from the advanced Hellenistic and Roman periods. It should be clear that the “perception” of the scene as “ancient” or “old” is something extremely feeble and subjective, with a variety of elements that may influence the user to recognize as “coming from the past” a certain scene or at least stimulating the sensation of being in a context coming from the past. Indeed, the people living in the time of Priene have different ideas about the physics of light (Smith, 2018) but their perception and vision were not different from the present one, nor there are ele-

ments that allow to imagine any possible difference in the light that every day made the theatre visible today or more than two thousand years ago. Thus, thanks to decades of architectural graphic (and recently, digital) reconstructions in museums, movies (Ramosino, Dognini, 2004) and games, there is a consolidated point and “taste” in the collective imagination that made certain colour scales and soft lights typical of a scenario offering a reconstruction from the past. The following steps are then all aimed in finding a satisfactory characterization that just suggest a context leveraging on these factors, allowing delicate pushes to the users toward the perception of the context. In these the use of software like Blender, with an accurate control on texturing and light effects hallowed to quickly reach a satisfactory result, with a light and a general colouring that may result compliant of scenario from the past even when presenting a completely reconstructed digital model (Fig. 6).

Sculpting and morphological variants

Although typological objects had been modelled correctly, they initially appeared too “perfect”, too “sharp”, and then too “artificial” when compared to the real appearance of stone blocks. This obviously bring to one of the many issues of digital reconstruction, the users are expecting an “old” characterization that is recognizable because of a certain level of decay, which thing should not exist at the time when the theatre was just new. Thus, the alteration of the general perception caused by a full “as-new” aspect is clearly working against a positive result in terms of fascinating and stimulating interest in the virtual model. For this reason, each object underwent a sculpting process (Greer, 2022), which involved temporarily increasing polygon density in order to add micro-irregularities such as chipped edges, abrasions, small fractures, and depressions. The work was carried out using a graphics tablet, treating the elements as proper digital sculptures.

From each base object, several variants were then produced, differing in the intensity of imperfections and fracture patterns. During scene generation, these variants were assigned to instances through a controlled randomization system, avoiding visual repetition and restoring the natural heterogeneity of the materials (Fig. 7).

Procedural materials

In parallel with geometric work, material definition was developed. Based on the photographic dataset from the survey, reference textures were created and integrated with procedural maps in Blender’s Shader Editor. Normal, roughness, and displacement maps were combined to reproduce the grain of the stone, surface absorption variations, and ageing effects.

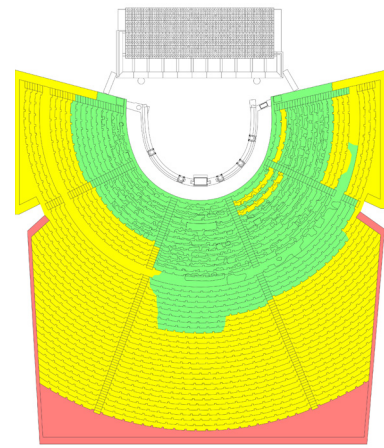


Figure 6. Overlapping match between the optimized model and the polygonal model from SfM/IM photogrammetry; overlap between the optimized model and the photogrammetric mesh of the existing state. The elements are distinguished by colour:

In Green – elements present and matching the survey;

In Yellow – reconstructions considered certain based on historical sources and structural symmetries;

In Red – hypothetical elements required for model continuity where archaeological data is missing.

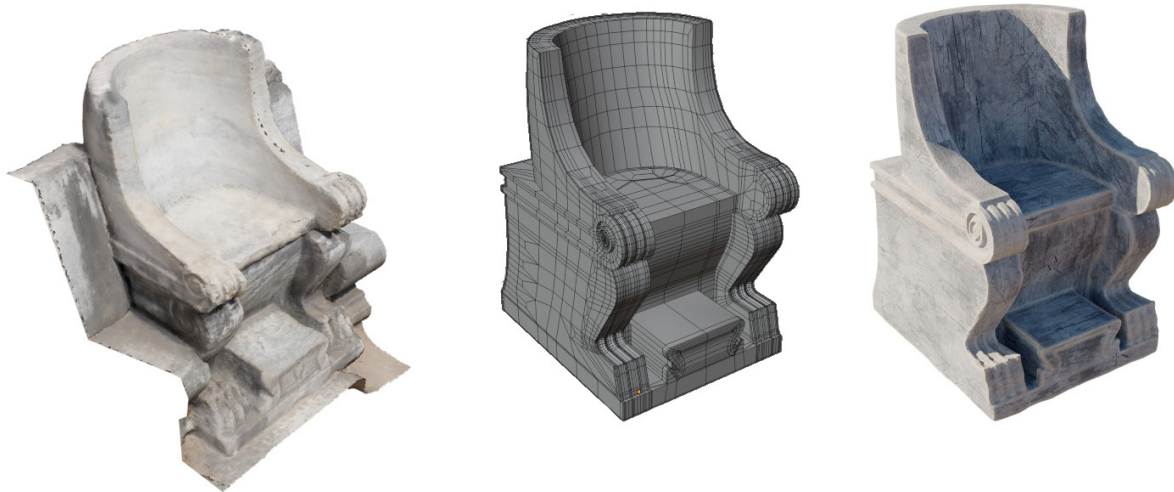


Figure 7. 3D model processing of one of the throne seat, refinement phase of the mesh of the throne's construction detail for the final model. Starting from a simplified low-poly mesh, the model was voxelized for the sculpting phase to add topological details and then simplified and procedurally textured.

The procedural component, managed also through Open Shading Language (Gritz, 2020), introduced microscopic random variations in colour and roughness without requiring an excessive number of distinct textures. Here too, the link between material and instance is stored within the metadata, enabling controlled regeneration of the model in different environments.

Environment and context

The theatre was placed within a simplified environment reproducing the current landscape of the site, without reconstructing the entire ancient city to keep computational needs and complexity under control. The main slope, selected vegetation masses, and an HDRI-based lighting setup were modeled and calibrated to simulate neutral daylight. This configuration allows for a clear reading of the theatre's volumetry, cast shadows, and the overall visual effect of the scene reconstructed according to Gerkan's hypothesis.

Virtual Reality

The model, once prepared, was exported into Unity Technologies Unity for the creation of an immersive environment (Bond, 2017). The goal was to offer a virtual visit experience useful for comparing the current state of the ruins with the proposed reconstruction. The choice was for a classic immersive environment based on fixed point of view, which may appear a little "blocking" in front of the users' experience, but at the same time offer a certain "safety" in fixing the view in predefined point of view, avoiding the virtual visitor from moving across the seats with a difficult virtual movement or across them with an unrealistic effect, the chosen solution, instead, suggest the positioning of the visitors into points that are well compliant with the logic of "being in a theatre" with heights from the level of the ground that are "human"

and then correctly working in perception and understanding of the role of architecture in making possible to appreciate a show on stage.

Importing and optimization in Unity

Within Unity Technologies Unity game engine, an interface connecting several panoramic camera positions was created, the panoramic views were chosen corresponding to significant viewpoints: the orchestra, the proedria, the lateral sectors of the cavea, and the lowered viewpoint at stage level. Each position, deriving from an equirectangular image was transformed into a 360° panorama, allowing the user to explore the surroundings through gyroscopic sensors or standard joystick-based controls. The use of Unity simplified the production of a multi-platform solution, making it easy bringing it to mobile devices (and then exploiting the now common integrated gyroscope) or to desktop environments.

Interface and interpretative functions

The navigation interface features a simplified map of the theatre, with buttons enabling rapid selection of the desired viewpoint. The application was developed for Android devices and desktop computers, with the possibility of use both through VR headsets and in “flat screen” mode. This dual configuration makes it suitable for exhibition and museum contexts as well as for educational and research scenarios (Fig. 8). The resulting app can be used even in place, with no direct overlapping of the reality, but giving an additional perception of the original aspect of the place that appear completer and more versatile than a standard panel physically placed nearby the entrance of the ruins. The Android version of the APP can be directly downloaded from <https://www.didalxr.it/digitaltheatreofpriene.zip> (following the classic instructions for the setup of external apps in the Android operative system).

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Figure 8. Metadata sample from the optimized modelling, export scheme of metadata in XML format. For each construction element, the reference model and its spatial instance are defined. Through an open-format metadata representation system, it was possible to make the model interoperable across multiple software environments.

Conclusions

The work carried out on the Theatre of Priene shows how the integration of historical sources, photogrammetric survey, procedural modelling, and virtual reality can generate a digital model that is not merely a three-dimensional replica, but an actual tool of knowledge. The centrality attributed to Armin von Gerkan's reconstruction hypotheses for the scene, verified and integrated in light of the survey and the documentation of Wiegand and Schrader, demonstrates how digitalization does not replace archaeological judgment, but makes it more readable, verifiable, and communicable.

The decomposition of the theatre into typological objects and instances, described through XML metadata, enabled the construction of a scalable, updatable, and interoperable information model across different software environments. The rendering phase in Blender transformed this abstract model into a photorealistic scene able to convey the material quality of the marble, the imperfections accumulated over time, and the spatial articulation of the complex. The implementation in Unity finally made the theatre an explorable environment.

In this sense, the Theatre of Priene becomes a laboratory for defining procedures that can be transferred to other contexts of archaeological heritage: a method that starts from historical documentation, compares it with digital surveying, builds a transparent procedural model, and returns it in accessible and immersive forms. The scene, which in antiquity hosted theatrical performance, became today a space for the representation of knowledge, no longer only a place of spectacle, but an interface between data, interpretations, and contemporary audiences.

From a methodological point of view, one of the most significant outcomes is the possibility of keeping three levels separate yet in continuous dialogue: the measured data, its geometric abstraction, and its immersive translation. The transition from the survey to the VR scene does not occur in leaps, but through a chain of traceable transformations, each of which leaves a "signature" within the metadata. This makes the model not only reusable but also open to critical revision: a hypothesis can be replaced, a parameter updated, an entire section regenerated without having to start again from scratch. In a context where technologies evolve rapidly, this capacity for adaptation becomes a fundamental requirement for any digital archaeology project that aims to endure over time.

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