THE GRUMENTUM'S ARENA: MEASURE, GEOMETRY AND SHAPE

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ABSTRACT:

In last years all the activities developed in the cultural heritage field have shown the necessity to integrate different analytical methodologies and technologies to obtain a cognitive apparatus of our architectural monuments, both from geometric and materical-figurative aspect.
The research on the archaeological site of the roman city of Grumentum (Basilicata) proves that reconstructive hypotheses can be obtained by an *iter* of study based on three fundamental instruments for architecture's knowing: measure, geometry and shape.
Measurement: a combination of techniques (laser scanning, digital photogrammetry, gps) can offers a suitable cognitive system to extract a numerical model to document the state of conservation of architecture. Considering the complexity and wealth of archaeological sites, In addition to the use of survey as a study of the city and the architecture, we need to use survey as a multiscale "receptacle" for categorizing the emerging objects, in its instrumental use in archaeological disciplines.
Geometry: on the base of survey data (mainly laser scanner data), geometrical tests can be done to verify which curves subtend the arena's inner shape and to fix a geometrical module to dimension each single part of the building.
Shape: integration of previous analyses and the comparison with other examples of amphitheatres, that can be considered close to Grumentum's one, both geographically and temporally, allow to provide a reconstructive hypothesis of the roman monument.
The obtained info-graphic model represents an important tool for knowledge and memory of a place that can't be visible and usable, opening new possibilities in studying archaeological sites and finding new way of cultural heritage's spreading.

More and more frequently the adjective *numerical* or *digital* characterizes terms such as "survey" and "representation", underlining how instrumental and methodological evolution has brought a new approach into the field of cultural heritage documentation.
Among the numerous experiences – many of which are still in progress - several have had the purpose of studying, examining and developing the integration of techniques for geometrical survey and 3D reconstruction of places and objects, with special interest in metric questions, through a comparison between the "traditional" survey methods and the newest ones.
Recently, we have witnessed a fast development of 3D scanning technologies to understand shapes, including with high morphological complexity. This growth has asserted its efficiency as a method for analyses and conservation of cultural heritage.
The survey of Grumentum's archaeological site (Basilicata), case study and focus of the research project "*Archaeological and architectural survey and three-dimensional modelling systems. Laser scanning and photogrammetric techniques integration for multiscale and mapped 3D models*" (Prin04, principal investigator prof. Carlo Monti), might be viewed as an experimental study aimed at defining some protocols and specifications in survey and modelling, testing the latest instruments in the field of shape and colour documentation, studying new possibilities in representation which are alternative or complementary to traditional methods.
The research team intends to study such 3D models for representation of an archaeological area with its architectonic emergences and documentation of its present state (geometric model) as well as to support the analyses that other professionals in the field can carry out.
The opportunity offered by geometric 3D models that warrants extensive further investigation is the possibility of creating **multiscale models: t**he range of scales generally derive from the survey of objects at different nominal scale that traditionally need very different detail definitions, such as the entire archaeological site (scale 1:2000, 1:1000, 1:500), an individual monument on the site (scale 1:200, 1:100, 1:50, 1:20), or smaller objects such as statues or fragments of architecture (scale 1:10, 1:5, 1:1).
It's plain that georeferencing is the most important process, resolved by inserting local systems into "less local" systems where the "localism" is not achieved by different systems of coordinates but rather, by a different level of accuracy of the coordinates, depending on the possible resolutions of the model of each set object. This entails finding the model to singularly manage objects that contain other objects, while respecting the tradition and the canons of architectonic and archaeological representation.

Survey campaigns – August 2005-2006

The survey activities have been addressed toward laser scanning and photogrammetric data integration, particularly for horizontal elements (on ground level, excavated or collapsed).
As a result, the main topographical network was divided into two schemes: the first, composed of 12 net-points

fig. 1 from point clouds to DEM, to ortho-image of Grumentum forum

(benchmarks) in the *forum* area and developed along the *decumano*; the second of 5 net-points distributed around and inside the amphitheater ruins. Some of the net point coordinates were surveyed by GPS measurements (with Leica GPS System 500 and GPS1200) to ensure a common system of reference.

The whole topographical mesh, adjusted using the least squares method, supplied the coordinates of net vertexes with an accuracy of 3 mm2. Photogrammetric control points were also surveyed by topographical (Leica TCR1103 e TCRM 1103) and GPS (RTK system) measurements.

Laser scans and photogrammetric pairs for vertical structures were optimized, following and integrating the process used in architectural surveys.

In an archaeological site survey, the realization of a Digital Elevation Model is particularly interesting, because it can be obtained by laser scanning and aerial calibrated photos taken from a balloon.

Terrestrial scans had to ensure the ability to obtain a dense model with a high and uniform resolution of all the surfaces.

The laser scanner used in this research is the Riegl LMS-Z360i, a hybrid system incorporating a high-resolution calibrated camera, a Nikon D100 (focal lens 20 mm), into a laser scanning system providing a very efficient, convenient, and powerful system for automatically generating accurately textured high-resolution 3D models.

In the most interesting areas, scans attempted to ensure optimal orthogonally to surfaces, which is a necessary condition, as well as data redundancy to reduce noise, in addition to a homogeneous points distribution.

Point clouds (corresponding to 30 scans with angular step 0.005°) were aligned by using topographical control points and tie points located all around the scanned area. Accuracy in alignment is less than 1cm.

Balloon photogrammetry was used to guarantee high image resolution, especially for horizontal elements.

It's well known how photogrammetry plays a fundamental role in cultural heritage preservation as survey and detailed documentation method. Recently, orthophotos and photoplans have been routinely used, especially in the archaeological field, just because they offer an effective tool for metrical and material analyses: nadiral view, combined with high quality photographic images, makes it possible to read and explain what can't be seen from a terrestrial point of view.

In fact, in archaeological survey, we lose all of our points of reference: there is no architecture, only fragments of architecture, in the best cases of the ruins. In survey of plans and façades reduced to a ruinous state, it can be difficult to find certain references (horizontality, verticality, symmetry, parallelism) to use as guides in the production of a survey. Frequently, the surveyor can scarcely even imagine a representation of the ruins in relief that are being observed. An aerial view can guide in the comprehension of the architectural composition of a place.

In the case study of Grumentum, photogrammetry had to supply all the supports for a multiscale "site-monument-trace" reading.

fig.2 aerial strip by baloon of the anphitheatre

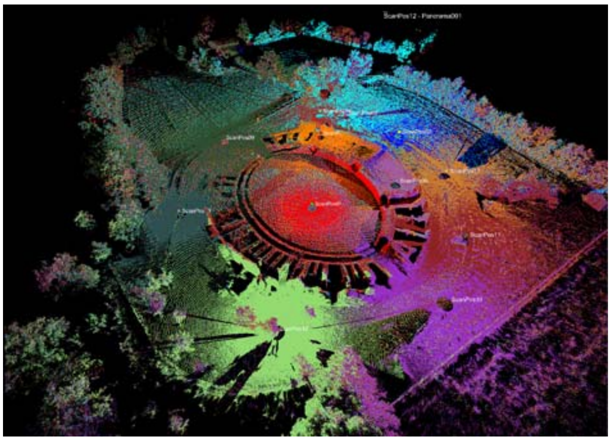

fig. 3 Alignment of all the scans in amphitheatre area

Image resolution had to ensure metrical as well as descriptive accuracy, considering different levels of detail. This is why "non-conventional" photogrammetry was chosen.
As we can see from other survey experiences, aerial shots can be done by helicopter, aerostat or other elevation devices, depending on the range of the coverage and environmental conditions. In this study, it was decided to employ a moored balloon for the photogrammetric strips equipped with a calibrated high-resolution camera, as this is one of the most controlled and non invasive methods. The aerial system was composed of a small helium-filled airship, restrained by cables anchored to the ground and a radio-controlled device for image acquisition. A digital camera (Fuji S3 with 12 Mpixel resolution and calibrated focals of 50 and 20mm) plus a video camera for the shots ground control were connected to the balloon through an adjustable platform.
Due to the range of the archaeological area (forum and amphitheatre) the flight was planned to obtain 1:50 – 1:100 scale images.
System limitation was due to the instability of wind conditions, especially for the flight attitude: corresponding to a multiscale acquisition, our altitude was about 20-30m, for better stability and control of the airship.
In the second survey campaign (August 2006), photographic integration of the site was done by an ultra light aircraft from a flight altitude of 200m.
The orthophotos of the whole site were obtained by laser scanning DEM and aerostat photos. Nominal scales of representation range from 1:200-1:100, for the site, to 1:50 for each architecture.
Main problems were the well-known errors due to surface discontinuity (breaklines) and hidden areas. Breaklines can be solved by working deeply on DEM data, integrating laser scanning data with topographical points; while the second question can be overcome by using much more oriented images, to guarantee a more complete coverage.

Geometry

The ancient Romans loved symmetry, not so much as an equivalence of parts of a figure with respect to one or more axes, but as the harmony of numbers, measures and proportions.
Vitruvius always supported this concept by talking about the purpose of symmetry and at the same time, he did not consider architecture as something abstract but rather like a concrete activity that must be adapted to the nature of the site and must be confronted with human needs.
When dealing with a structure such as an amphitheatre, Romans proposed different methodologies to tackle it. As an example, Mark Wilson Jones, a scholar of Roman architecture who recently collected hypotheses concerning designing amphitheatres, suggests searching for the shape of a plan, finding if it's an ellipse or an oval and once the geometrical reference is known, he suggests reconstructing the entire process determining the construction of the structure through the use of proportional and geometrical relations.
This kind of analysis would diminish, if not totally lose, the fundamental object of our studies: the survey.
Thanks to the certain data gained from the survey, it's possible to estimate which was the borderline between theoretical search of geometrical perfection and the realization of this concept in a building.
Starting from a critical analysis of data, it has been possible to recognize both the inner and the exterior profile of the amphitheatre, paying particular attention on the untouched elements.
Incorporation of different survey methodologies also made it possible to create a planimetry in which all the ruins of the amphitheatre are recognizable: from walls that are still intact (lines drew from laser scanner's point clouds) to traces of septa that are recognizable just for

different colours compared with soil (lines drew from the orthophoto).

The study has been developed according to the following steps:

- points of each curve were interpolated with ellipses and 4 arcs ovals and 8 arcs ovals, to estimate the standard deviation of every single figures
- using previous results, an interpolation of points was done with 4 arcs ovals and 8 arcs ovals but, this time, maintaining fixed the generating centres of spin, the generating triangle and the spin of axes, to being able to estimate the position of centres of spin that Romans used to drawing the figure on the stocks.
- The most probable coefficient was found for the conversion ratio from meters to Roman feet;
- radial convergences of building septa regarding the centres of spin of ovals were verified;
- the plan was redesigned, controlling the geometrical relationship previously reconstructed.

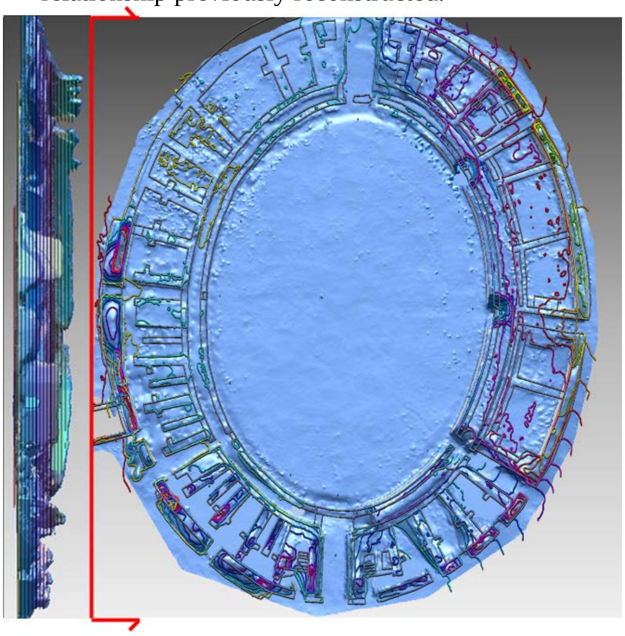

fig. 4 profile extraction from triangulated mesh

Final results, obtained by interpolation of curves and from the analysis of the convergence of septa, have shown that it's more reasonable to think that both profiles, the inner and the external one, had been drawn following the oval outline rather than the ellipse outline.

Therefore, after establishing the conversion coefficient metres/Roman feet that made it possible to determine the original dimension of two axes, it was identified into Grumentum's amphitheatre a modular tripartite outline, which is valid for plan (three modules of 30 feet each one) and for raised structure (three modules of 15 feet each one), developed from the model of Pythagorean triangle.

Corresponding to this hypothesis, once *in locus*, this scheme was simulated just to verified the congruence between the geometrical outline and the building itself. In fact, thanks to the coherence of data –referred to one common reference system- it was easy to materialize the previously calculated 4 centre of spin and to trace, starting from these points, the inner profile of the *cavea* just to find an actual adhesion between the building and the model.

Component and structural features

The Grumentum amphitheatre, though placed in a small settlement, shows the bulk of the elements which characterize the amphitheatres of the Imperial Age. The arena is a structure without sites of hypogeum. Around the arena, there is an annular corridor covered with a sort of barrel vault. Such corridor, which can be seen in elevation (fronts) only in the western part, was the supporting element of the podium, whose remnants can still be recognized.

The supporting structure is characterized by two different construction systems. In the Western part, it is defined by filled spaces that are separated by partitions with blind spaces, inaccessible from outside; in the Eastern part, is a completely different structure, made of self-supporting partitions. Above these partitions, the building should extend with sort of frustum-of-cone-shaped barrel vaults which themselves support the stands. In the Western part, the stands lean directly against the partition rooms. Cassino and Castra Albana amphitheatres are examples of buildings that show this sort of supporting system.

At the present stage, the existence of the stands is not noticed. We can suppose, however, that the *cavea* were characterized by a single *maenianum*, where it is possible to distinguish the *podium*, detached from the stands by a likely *praecintos* and by a corridor before the stands themselves.

We focus then on the distributive structure, where the tracks for the audience are well separated from the ones for the shows. The gladiators entered the arena from the main entrances, located on the major axis, or from the internal annular corridor, divided in two branches which could be accessed just from the openings in the major axis. In the western part, the access to the corridor was possible through a single opening reachable from the outside, while it is possible to enter from the eastern part, with the help of nine arches placed on the outer perimeter wall.

The customers' tracks were divided between stands accesses and podium accesses. In the Grumentum site it was possible to identify four stair flights in the external part, still visible, close to the main entrances. Analyzing the different parts of the amphitheatre, we suppose that such entrances consisted of two flights: the first for the podium and the second for the stands.

In the eastern part of the amphitheatre we recognize three radially oriented separators, probably corresponding to the stairs for the podium. The access to them, in the western part, was possible through two entrances placed at different heights on the outer perimeter wall. They are only partly visible and consist of two flights, converging on the landing placed above the arches at the entrance. According to the measurement, such arches would lead to a lower height, with respect to the one which is necessary to reach the stands. By the external landing, there would be therefore an additional climbing system inside the perimeter wall, crucial to reach the defined height. .

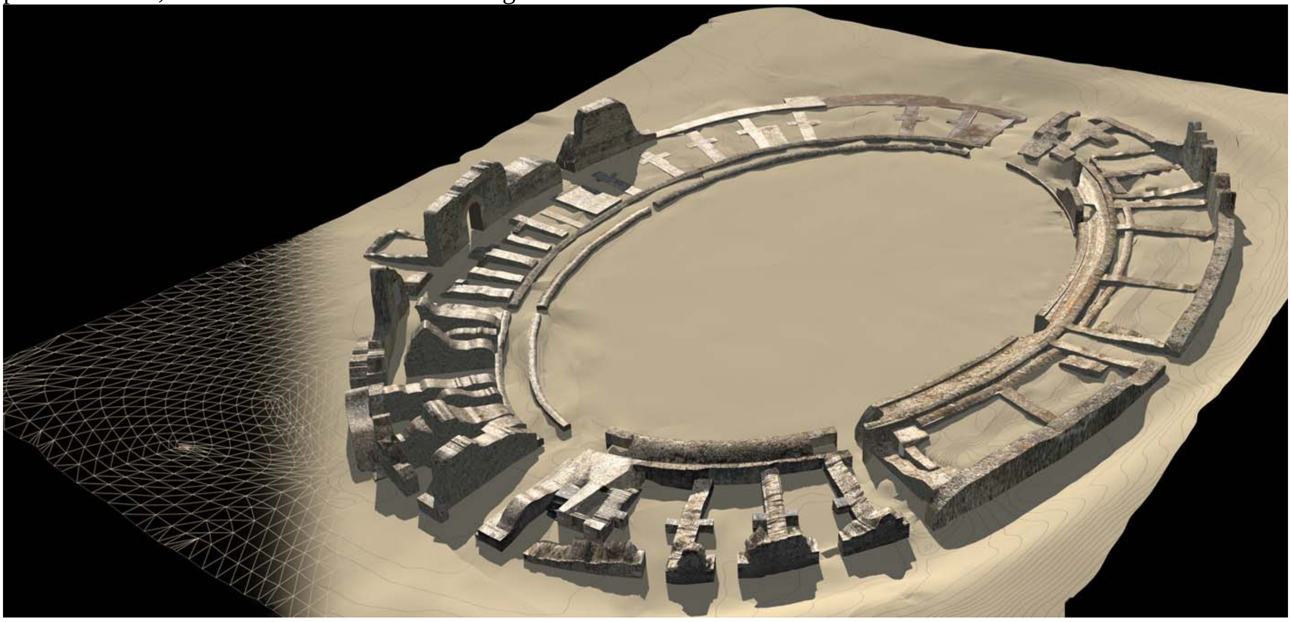

fig. 5 The 3D model representing the state of conservation of the amphitheatre. Model surfaces are texturizzated with rectified images

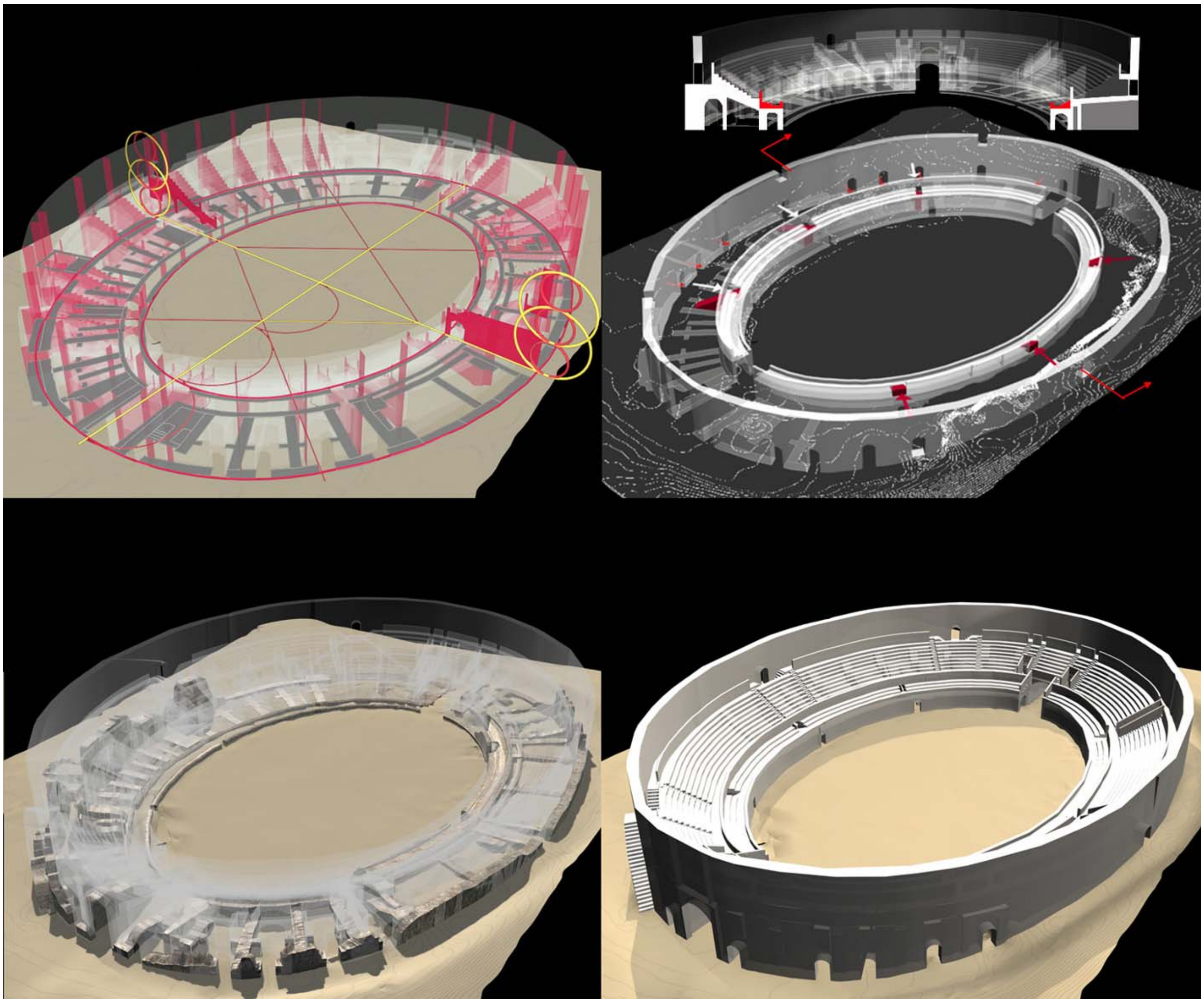

fig. 5. Digital reconstructive process of the roman architecture as the results of survey data, geometrical an typological analyses

The couple of stairs, which is present also in the western part close to entrance from the natural slope, is drawn on in the eastern part, close the aforementioned accesses. We suppose the existence of a continuous annular corridor, parallel to the outer perimeter wall, to connect the whole *cavea* with the upper part.

A similar kind of entrance has been recognized, in particular, in the Pompeii amphitheatre (which we have surveyed) and in the Carsulae and Paestum amphitheatres.

Digital reconstruction

3D modelling and photorealistic rendering occupy a definitely wide section of informatics' technologies applied to archaeological - historical resources. They play the main role in making it easier to understand a place and pointing out relations between each single component element.

Of all possible representations, three-dimensional models, presenting high resolution and photorealistic texture (picture mapping), produce very versatile elaborations, with a new perspective: providing a database to document current conditions of a place and to offer the possibility of interpretation of its original state and its transformations through its still visible monuments.

For the site of Grumentum, the state of conservation was supplied with 3D representation, 3D surfaces (mesh) obtained by lidar data and calibrated images (as textures): descriptive and geometric qualities are given by summing geometric to raster elements. Actually both components have to be balanced in multi-resolution mapped models in order to maintain metric and semantic- perceptive characteristics, respect the nominal scale of representation, and to gain the 3D reconstruction of the original shape (Balletti et al. 2006).

Specific modelling processes were concentrated on the amphitheatre structure, which is the most interesting monument from the architectural point of view for a geometrical and spatial analyses, founded on a comparative typological approach.

The main difficulty was modelling of real shapes with all their "deviation" from a rigid geometry, to ensure the requested accuracy, and the "re-deign" the more original look of the amphitheatre on this irregular base considering all the constructive and distributive components characterizing this architectural typology.

A triangulated surface model was obtained (about 1.85 millions faces) from laser data (about 3 millions points), as a geometrical support for thick profiles extraction. Profiles were used in solid modelling (CSG) to better represent collapses.

The 3D model representing the present state was texturized by mapping rectified images of the vertical fronts and orthophoto (on collapsed irregular surfaces). Images have a pixel size referred to real of 1 cm. Since the amphitheatre is partially located on a sloping surface, a digital terrain model was obtained through laser data triangulation. When properly processed, this mesh was then converted in a nurbs surface to ensure smooth level and patch continuity, obtained with difficulty from a gridded DTM. Besides nurbs geometry guarantees geometrical continuity and congruence between DTM and architectural model.

Thanks to survey data and their interpretation, a philological 3D reconstruction of the amphitheatre was reached, representing both memory of a place (suddenly archaeological site are "invisible") and a knowledge and communication tool to be employed in many scientific fields.

Assuming the point of view of an architect with respect to a reconstructive activity (re-design) of an ancient architecture, some fundamental principles were identified and considered during modelling processes:

- geometrical congruence with reference to objective information reached by digital survey;
- constructive congruence with reference to ancient Romans technologies, that is deducing the amphitheatre shape by an effective constructive possibility, based on current structural reading;
- form congruence with respect to typological comparison.

The final 3D model brings the amphitheatre back not only to its former shape, but to a three dimensional transposition of direct and indirect information obtained using different methodologies of analyses, which had supported all the choices in the project.

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