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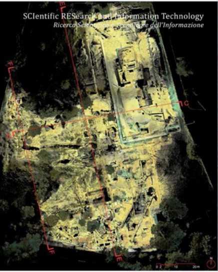

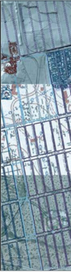

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NEW ANALYSIS ABOUT ARCHAEOLOGICAL ARCHITECTURE (AA): SIX ANCIENT THEATRES OF THE MEDITERRANEAN SEA

*Carlo Bianchini, Carlo Inglese, Alfonso Ippolito**

*Sapienza University of Rome – Rome, Italy.

Abstract

The promotion and preservation of Cultural Heritage in the 21st century are inextricably bound up with innovative processes of acquisition, management and knowledge. Continuous technological progress and the digital revolution offer new tools and possibilities that can be applied to research. The development and enhancement of techniques for the mass acquisition and processing of this data creating 2D-3D models has made these processes fundamental to disseminating information on Architectural Archaeology.

This paper describes the most recent results of the research activities originating from the Athena Project (Ancient Theatres Enhancement for New Actualities), which has entailed the study of six of the most famous Mediterranean Ancient Theatres: Mérida, Petra, Jerash, Carthage, Cherchell and Siracusa.

Keywords

Archaeological architecture, ancient theatres, survey, 2D/3D model, architectural proportioning, database

1. *Introduction*

Ancient Theatres are one of the most extraordinary legacies bequeathed to us by the Greco-Roman civilisation: culturally, due to the important role they played in the social life of several cities; environmentally, due to the criteria and care taken to optimise the impact of these structures on the territory and urban context (Neppi Modona, A., 1961); technologically and functionally due to the quality o*f their acoustics and layouts* (Fiechter, E.R., 1914; Anti, C., 1947; Ward-Perkins, J.B., 1974). The interest and 'success' of Ancient Theatres among the public at large is certainly one of their strengths and the key reason why they survived (Marta, R., 1990; Sear, F.B., 1990; Ciancio Rossetto, P. & Pisani Sartorio, G., 1994-1996; Gros, 2001; Pappalardo, U. & Borrelli, D., 2007). However, this 'success' is also the primary reason for their decay. The relentless pressure exerted on these structures by the passing of time, exceptional natural events (geological, meteorological, etc.), contemporary use (tourism, performances, setups, etc.) and war-related or socio-political events were unfortunately increasingly frequent, leading to the slow, but often irreversible deterioration of these architectures.

In the past twenty years, beginning with the Declaration of Segesta (1995) and more *recently the Siracusa Charter*[1] (2004), Ancient Theatres have become an important issue in the debate about Cultural Heritage especially in the quest for balance between strict conservation and sustainable usage. It is right in this framework that we will present the results of the documentation and analysis performed on the theatres of Mérida, Petra, Jerash, Carthage, Cherchell and Siracusa (Morachiello, P., 2009; Pedersoli, A. & Paronuzzi, M., 2010) as part of the EU ATHENA Project (Ancient Theatres Enhancement for New Actualities)[2] (Fig. 1).

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[1] Charter for the conservation, fruition and management of ancient theatrical architectures in the Mediterranean <http://www.univeur.org/cuebc/downloads/PDF%20carte/18.%20Carta%20di%20Siracusa%5B.pdf> [September 2016].

[2] The ATHENA Project (2009/2013, with a budget of roughly 1.8 million euro, <www.athenaproject.eu>) was financed by the European Commission as part of the Euromed Heritage IV Programme (<www.euromedheritage.net>), the fourth step in an intervention package originally created by the EU in the framework of the MEDA programme and under the supervision of the EuropeAid Cooperation Office. Since 1998 Euromed Heritage has spent roughly 57 million euro in the field of Cultural Heritage, financing cooperation projects between various actors from different countries in the

Mérida Petra Jerash

Carthage Cherchell Siracusa

Fig. 1: The Theatres of the ATHENA Project: Mérida, Petra, Jerash, Carthage, Cherchell and Siracusa.

The project has helped to draft a new, updated strategy for the documentation, conservation, enhancement and sustainable fruition of theatrical structures by turning some of the recommendations of the Siracusa Charter into concrete actions. Not just as proposals or design projects, but by working in corpore vivi in six particularly emblematic sites all belonging to the UNESCO World Heritage List (Bianchini, C., 2012).

2. Background

Survey can be considered as a knowledge tool to understand material elements, i.e., the process that materially envisages the establishment of a suitable Knowledge System to acquire, select, interpret and represent quantitative but above all qualitative information (Docci, M., Bianchini, C. & Ippolito, A., 2011). It is an intrinsically multidimensional and multidisciplinary process[3],

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Mediterranean (research agencies, universities, administrations, scholars, local communities, etc.), actors who are involved one way or another in the documentation, conservation and management of Cultural Heritage. Almost 400 partners on both sides of the Mediterranean have benefited from the first to the fourth Programme and, currently, the last edition.

[3] A multidisciplinary approach is now a basic requirement in any study, while as far as multidimensionality is concerned we should examine several fundamental concepts linked to the so-called culture of the control of space in which it is possible, amongst other things, to identify the following principles: human beings have an innate or acquired ability to mentally imagine the qualities of physical space; from amongst the n qualities of physical space, geometric qualities optimise control and manipulation; manipulation and modification of space become tangible thanks to correspondence between the real object and its geometric abstraction (Geometric Model); when the Geometric Model is subjected to the representation process according to the rules of the science of representation, it becomes a two-dimensional Graphic Model and drawing is the tool that ensures the efficiency of the mechanisms of control and manipulation of the graphic model; when the Geometric Model is virtually reconstructed using modelling software it becomes a 3D digital model. Based on this approach, the multidimensional reality of a given object is reduced to its geometric essence, i.e., the Geometric Model made up of

which in the case of archaeological objects involves not only the study of their tangible characteristics (geometry, construction, conditions) bu also their *intagible* ones associated with history and cultural and social context.

In some ways *Survey* involves capturing the intimate essence of material elements, understanding their structural matrix and proportional ratios, not to mention what is often concealed but linked to the intangible culture which, over the centuries, has produced, transformed, preserved and finally enhanced those elements. In this regard, the survey process is closely linked to the epistemological concept of *model*, considered as the outcome of the operation performed by an actor on an object to extract some of its endless data. Some representations, for example the so called *graphic models of space*[4] have, over a period of time, been cleansed and stratified in forms which, by optimising univocal data transmission, have turned the model, even from an operative point of view, into a virtual substitute of the object still widely used to simulate the most diverse operations. Nevertheless, the advent of digital systems has added new 3D models, numerical and mathematical[5] (Migliari, R., 2009) to traditional (intrinsically 2D) *graphic models*. These new *3D models* are purely numerical representations which, however, are capable of establishing a very precise correspondence between physical and virtual *space*[6]. Furthermore, they are basically free of the dimensional constraints imposed on a traditional drawing by the limited size of the support. However, the digital revolution has influenced the field of Survey also and above all as regards the Data Acquisition phase. In fact, we now possess a whole range of tools and technologies that in just a few short seconds capture the geometry of any object, with errors that are easily less than one millimetre and without losing any information regarding the most important characteristics of the surface (colour, reflectance[7], etc.). No-one can deny there is a clear-cut boundary between acquisition/representation procedures – all tendentially focused on 'maximum objectivity' - and interpretation which is instead the phase during which the subject remains the protagonist (Bianchini, C., Ippolito, A., & Bartolomei, C., 2015). Having established this boundary, some segments of the process appear capable of overcoming the stringent requirements imposed by the Scientific Method[8] that other disciplinary sectors normally use in their research activities. The Data Acquisition phase (Fig. 2) obviously includes the concept of measurement, i.e., the operation that makes it possible to translate the *quality* of a phenomenon into a *quantity* expressed using numbers derived from the relationship between the quantity surveyed on the object and the chosen unit of measure. In the field of *Survey* this procedure has been historically governed exclusively by a trained surveyor. This is true for direct surveys, but is less so for topographic surveys: it's true that the operator chooses what he wants to measure, but he does not measure it himself, he simply uses a device: the distance meter. Previous statement is even less true when laser scanners are involved: in this case the operator neither influences the

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points, lines and surfaces which, appropriately scaled on the support and then projected and sectioned, in turn produces the graphic representation. In other words when it is reproduced in virtual form it creates a 3D Digital Model. In any event, this procedure establishes a biunivocal correspondence between the object and its virtual substitute on which to simulate any number of operations as if they had actually been performed.

[4] One example are the so-called graphic models of space which, based on the strict geometric-projective procedures of the Science of Representation, establish a biunivocal correspondence between the object and the two-dimensional model.

[5] We summarily classify models into 2D (graphics) and 3D. In turn the latter can either be material (i.e., traditional maquettes/the more recent 3D prints) or immaterial, expressed as digital numerical aggregates.

[6] Each material point Pr identified using its coordinates x_r,y_r,z_r in real space, immediately finds its virtual equivalent Pv, also identified by a univocal triplet of Cartesian coordinates x_v,y_v,z_v.

[7] Reflectance indicates the portion of incident light that a given surface is able to reflect. The value has a physical significance associated with the characteristics of the material when its surface is hit by the scanner.

[8] Karl Popper acknowledged the intrinsic inappropriateness of the tools available to humans so that they can understand reality and, ultimately, the very real inability to 'positively' demonstrate any statement as true. As a result he shifted the barycentre of knowledge towards proving that something is false. Popper believed that any theory is scientific only if it is possible to consider experimental activities as having the following objective: to demonstrate its inadequacy, i.e., its falsity. Based on this hypothesis, the study of a phenomenon is considered scientific only when a set of techniques is used and the latter are based on collected data that is observable, empirical and measurable, with an established level of controlled and declared level of uncertainty; it must be possible to file and share this data as well as allow it to be independently assessed; the procedures must be repeatable so that a new set of comparable data can be collected

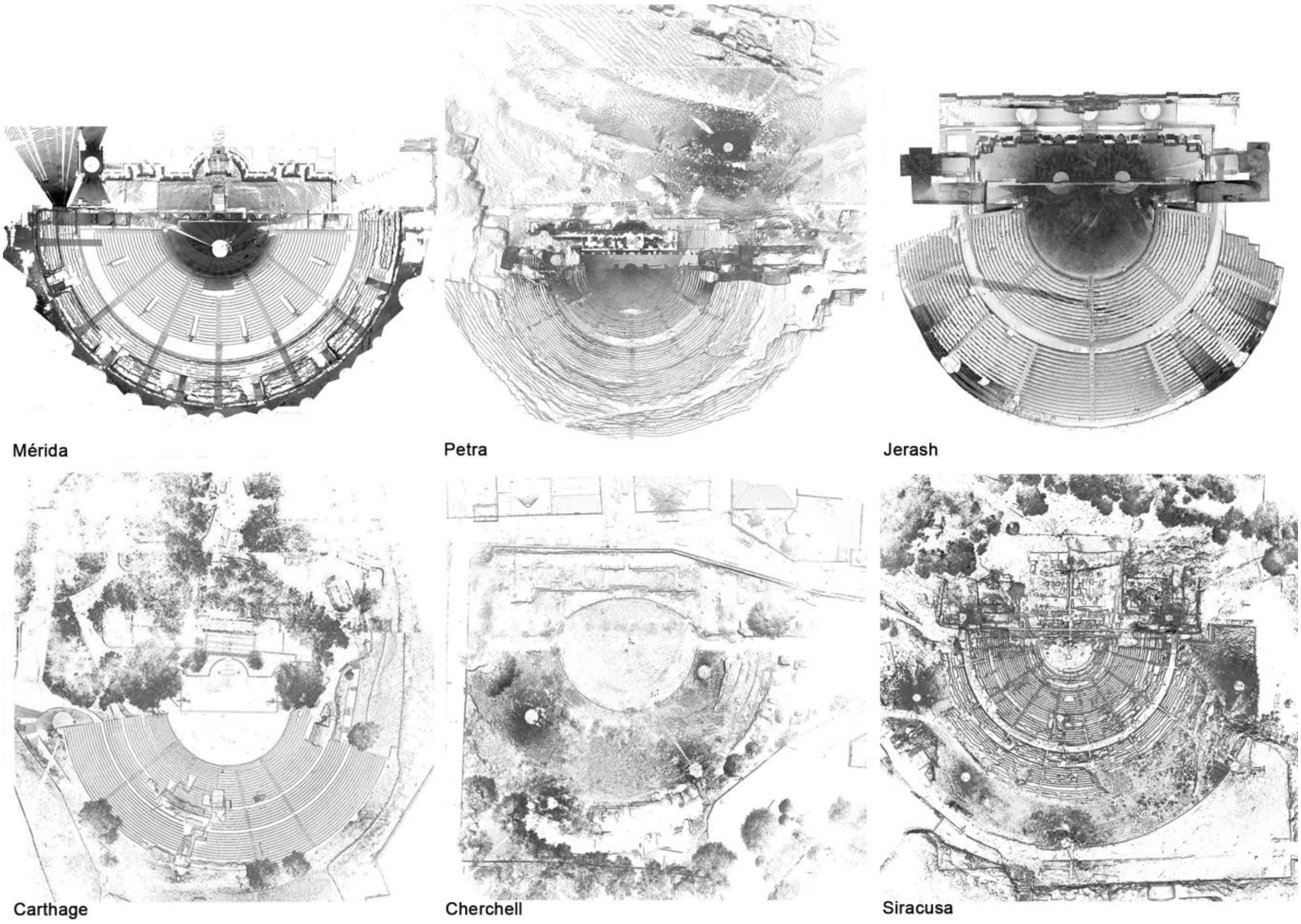

Fig. 2: The Theatres of the ATHENA Project, data capture.

measurement nor does he choose what to measure. It all depends on the sample spacing and the distance from the surface hit by the laser beam. So, depending on the applications, the process shifts between *semi-automatic* and *totally* automatic (in the future this latter mode will probably be widespread and ubiquitous).

This trend towards an automated acquisition phase is not the only purely technological aspect we need to bear in mind (Bianchini , C., Borgogni F., Ippolito A., & Senatore L. J., 2014). There is another phase we could call the 'democratisation' of survey technologies. Its technological basis is the so-called *Structure from Motion* (SfM): not a collimated ray, emitted by a source, that hits a material aureole and is recaptured by a sensor measuring a certain physical parameter (time of flight, phase difference, angle of reflection, etc.), but a light ray 'naturally' emitted by that same aureole towards a sensor. Obviously, one ray does not determine the 3D position of the point from which it is emitted (the same univocal correspondence linking a point and its perspective representation), but nevertheless when several rays are emitted from the same point we can find the 3D position using an inverse intersection procedure (Green, S., Bevan, A. & Shapland, M., 2014).

This situation raises the issue of how surveyors interact and manage these technologies and devices. Furthermore, all 3D acquisition systems produce a huge amount of data and much of these are extremely redundant.

Opposite to the Data Acquisition, the procedure of Data Selection will never be automatic or even semi-automatic because it is closely linked to the aforementioned concept of *model*. This is the reason why all the 2D and 3D *models* are very important: not only as a basic map or hypothetical reconstructions of the sites (for which we often lack reliable, updated drawings), but above all as the result of a critical process directly linked, *hic at nunc*, with our ability to select and interpret the sites based on available data (Gaiani, M., Benedetti, B. & Apollonio, F.I., 2011).

3. Data Capture

Data capturing increasingly involves the use of integrated technologies to acquire a large number of points; this technological phase is conceptually and operatively different from traditional methods still widely used in archaeology. In traditional survey processes, be they direct or instrumental, the data acquisition phase is preceded by a careful preliminary study phase; the latter controls the limited measurement options through prior selection of the significant points and discontinuities that will later be measured. Therefore, selection *precedes* measurement, almost as if in the surveyor's mind the survey already existed and only needs to be confirmed (or disproved).

Furthermore, the use of traditional survey instruments and procedures has often been hampered by the physical difficulties associated with covering an archaeological site that is either very big or has complex geometries. Recent technologies, such as 3D scannning[9] or *SfM*[10] allow the surveyor to acquire the millions of points he needs to provide a good description of the surfaces without having to establish in advance which ones need to be measured.

This phase still involves dealing with certain key methodological issues: the type and complexity of the object to be analysed, the potential and limits of the different instruments, their correct use, and how they affect the speed and quality of the survey and data processing and restitution phases.

Since each archaeological site has its peculiarities, it is impossible to establish an absolute rule regarding the way a survey should be performed. Nevertheless, all the methodological options are analysed and developed during the survey project in order to optimise the operations vis-à-vis the objective. As a result, elaborating a *survey project* is a key stage in every *scientific* survey. This is when the objectives are established and a decision is taken regarding the instruments, the representation scale of the drawings, and the number and position of the various stations. A correct survey project (partly) guarantees the quality of the data later used to produce the survey drawings; it also ensures the accurate gathering of numerical data resulting form the measurement operations.

Today the option to integrate different data acquisition methods is a consolidated practice extensively used in the field of archaeology. Integrating different acquisition and processing modes means exploiting each instrument's potential to the full, enhancing its qualities, compensating its limits, and merging the ensuing data with the data acquired or acquirable using other techniques (Brunetaud X., De Luca, L., Janvier-Badosa, S., & Beck, K., 2012).

As regards the theatres in this study we decided to use an integrated 3D survey to gather as much data as possible about the objects' surfaces. Our objective - to elaborate a good operative protocol to survey large-scale archaeological complexes - significantly impacted on our choice of methods and techniques. Although these theatres were all the same type and were used for the same purposes, they differed in their metric and geometric characteristics, discontinuities, materials, colours and state of conservation. In addition, the limited time we had to survey each theatre forced us to establish minimum objectives by immediately defining a set of data acquisition parameters. Our choices were further influenced by the fact that we would later have to elaborate 2D and 3D

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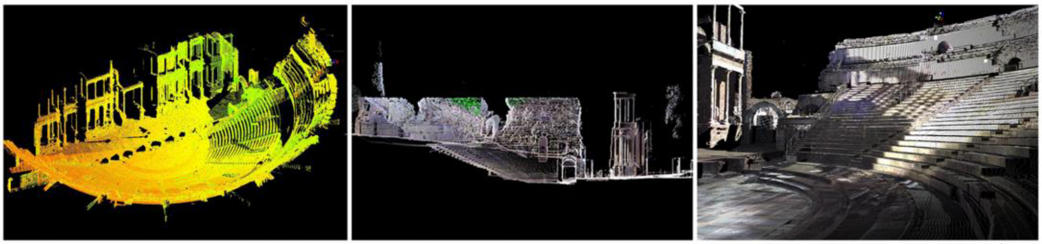
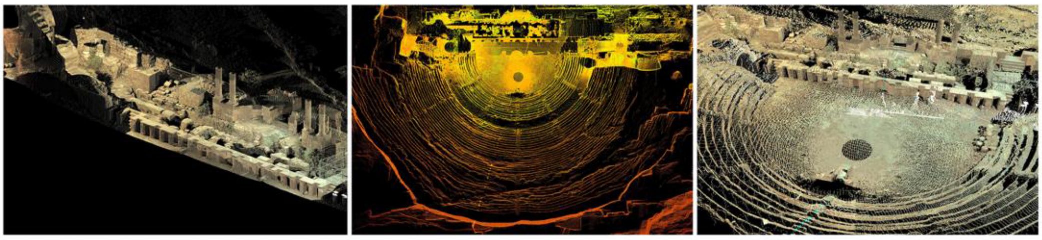
[9] In the theatres in question we used a time-of-flight 3D laser scanner; this device sends out electromagnetic pulses (lasers) and captures the signal reflected from the surface that is hit. This operation measures the round-trip time it takes for the pulse to reach the surface and come back to the instrument, i.e., the distance between the instrument and the surveyed point. Using these devices it is possible to very quickly acquire extensive data: the result is a huge set of points (points cloud) distributed over the object to be surveyed, with a reading that varies according to the amount of detail one wishes to record. Every point is characterised by five data: three numeric data, the coordinates x,y,z, referring to the coordinates of the scanner; a RGB data that positions on the point the data of the photograph acquired by the instrument; another RGB data, reflectance, corresponding to the amount of energy that is emitted by the instrument and returns once it has hit the surface to be surveyed.

[10] Structure from Motion technologies (digital photogrammetry, photomodelling) were developed based on the theoretical premises of photogrammetry. It permits the restitution of 3D graphic models by merging survey, modelling and representation; this is achieved by extracting coordinates, distances, vertexes and profiles from the photographs. The highly automated process is what makes it innovative, i.e., the possibility to obtain not only a large amount of data in a short space of time, but also to create a model that includes the geometric and qualitative characteristics of the analysed object.



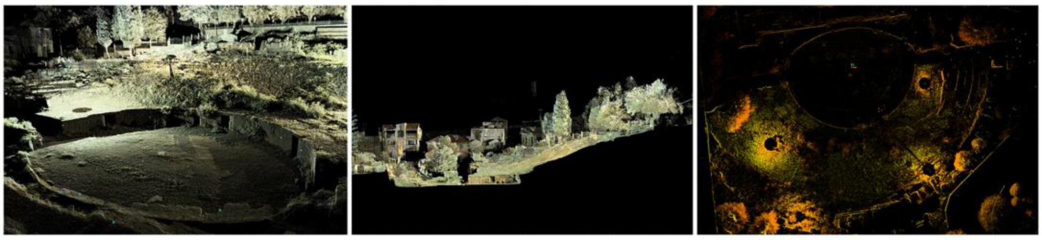
Mérida



Petra

Jerash

Carthage



Cherchell

Siracusa

Fig. 3: The Theatres of the ATHENA Project, numerical models

models with similar and therefore comparable characteristics. Establishing an acquisition process that could be repeated for the six case studies inspired us to obtain homogeneous models based on the same amount of data (Fig. 3) and representation type.

By integrating non-contact survey methods we were able to jointly use topographic instruments, 3D laser scanners and photographs. Before starting the project we established the criteria and the way in which we would use these instruments. Topography, for instance, was entrusted with the management and control of the uncertainty[11] of such a large-scale survey. We prepared a topographic polygonal that was either open or closed according to the requirements imposed by the surroundings; this allowed us to not only place each theatre in a rigidly-controlled grid, but also measure several important points selected directly on the object. In addition, we were then able to register the point clouds obtained with the 3D laser scanner in a single Cartesian reference system. In all the case studies we tried to make the position of the topographic stations coincide with the positions of the scanner; our objective was to obtain homogeneous numerical models[12] so that we could make comparisons.

We decided to execute not only general scans (1x1 cm sample spacing[13]) of all the sites to gather data regarding the size, morphology and shape of the archaeological complexes, but also detailed scans (2x2 mm sample spacing) for particularly important architectural/archaeological elements.

The numerical model was applied in the same way to all the case studies: the registration phase[14] was executed by directing the scanning according to the topographical reading. Since the points clouds were difficult to manage due to the size and density of the acquired points, they were suitably treated within the software[15] to eliminate excess data and establish data that could be later useful during processing. This was the last operation in the data acquisition phase; we continually controlled the registration error so as to maintain it below values in line with the uncertainty of the 3D scans(≤ 4 mm) and with the representation scale of the drawings (1:200 for geometric drawings, 1:100 for architectural drawings of the whole complex, and 1:50 for representations of details)[16].

4. Data Processing

Data representation is a complex phase, closely linked to what the surveyor wishes to communicate vis-à-vis the analysed object. This phase starts with a review of the acquired material and continues with an analysis of the artefact's unique elements; this is followed by an assessment of various issues based on the previously-established objectives and, possibly, the users to whom the final product is intended (Ippolito, 2007). When archaeological issues are involved the operator has to consider how he wishes to document, communicate and disseminate the information in a sector in which, compared to other sectors, the use of digital models has taken longer to become routine. Thanks to ongoing progress in the field of technology, data acquisition operations and processing procedures are increasingly entrusted

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[11] The instrumental uncertainty for the Leica Geosystem TPS800 total station is equal to a tenth of a millimetre.

[12] Numerical model is a mathematical summary of the survey data. All the information, whether metric or chromatic, is transcribed and registered in concise tables in which every line refers to a single measurement and every column contains numerical values relating to spatial data: XYZ coordinates and, where envisaged, chromatic coordinates

[13] Sample spacing is the size of the scanning grid. The perfectly regular grid established by the selected sample spacing will maintain the set distance only on a theoretical sphere, while in reality, the distances between the scanned points will vary on the basis of the position of the plane on which they lie. However, as the reality surrounding us is unlikely to reflect such a rigid geometrical pattern, we will have to deal with environments that are anything but spherical, consisting of planes at different relative distances and orientations.

[14] This operation makes it possible to unite the scansions based on a single reference system.

[15] *Clodworks*, the Leica Geosystem application.

[16] The survey was performed by Carlo Bianchini, Carlo Inglese, Alfonso Ippolito, Mario Docci, Chiara Capocefalo, Luca J. Senatore, Alessandro Cappelletti, Francesco Cosentino, Francesca Porfiri (Sapienza University of Rome), Filippo Fantini (Alma Mater Studiorum University of Bologna), Maysoon Qatarneh, Mahmoud Al Arab, Jamal Safi, Tawfiq Mahad, Marwan Asmar, Naeem Bani Salman (Jordan Department of Antiquities).

Numerical models obtained after data registration of each scan are homogeneous than the amount of acquired data. In order to reveal the process, shown below the data gained of each theatre.

Mérida: 23 scan stations; 23 topographic stations; point cloud: 800 million points.

Petra: 10 scan stations; 6 topographic stations; point cloud: 600 million points.

Jerash: 22 scan stations; 7 topographic stations; point cloud: 550 million points.

Carthage: 16 scan stations; 16 topographic stations; point cloud: 487 million points.

Cherchell: 6 scan station; 6 topographic station; point cloud: 420 million points.

Siracusa: 22 scan station; 15 topographic station; point cloud: 332 million points.

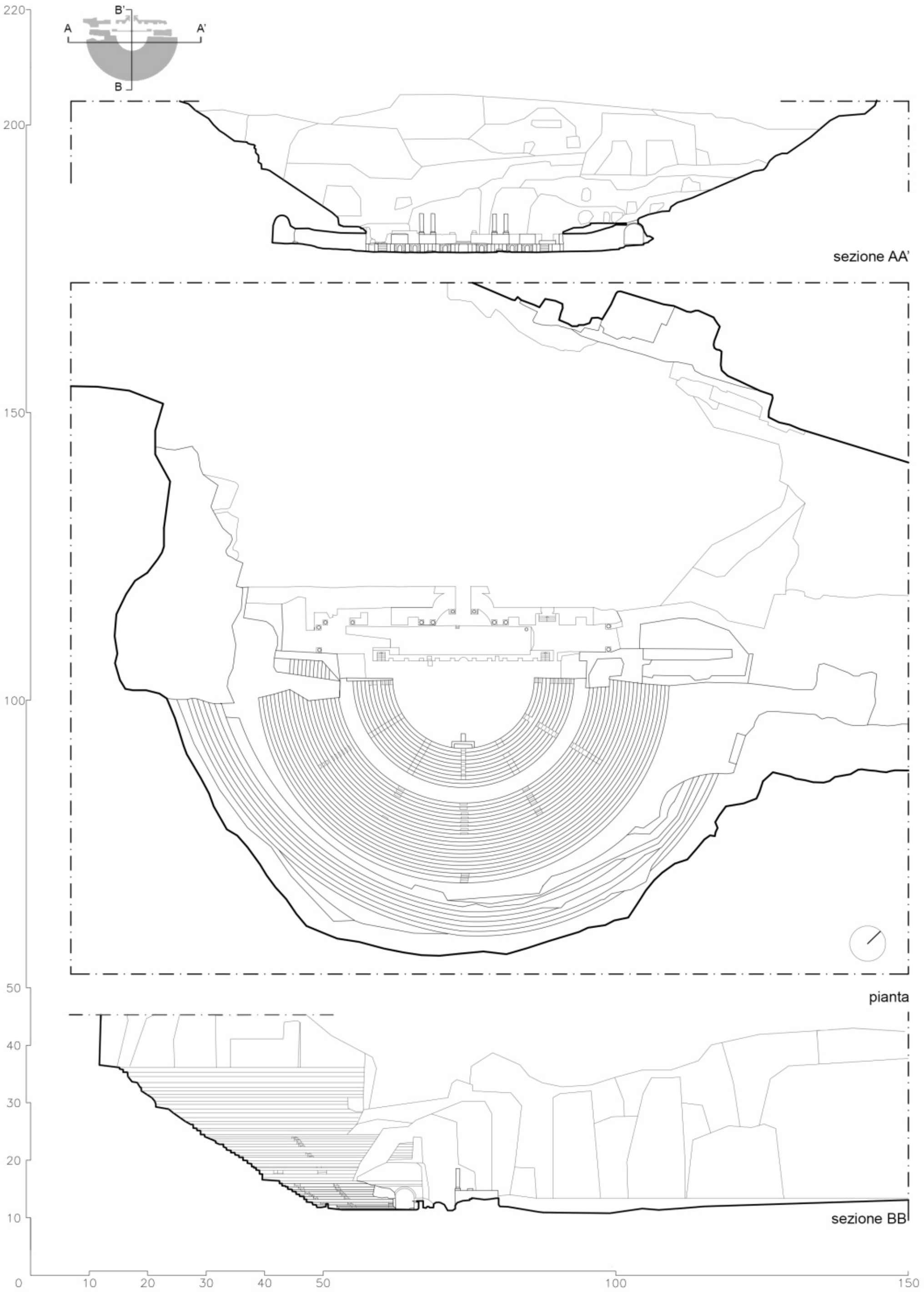

Fig. 4: The Theatre at Petra, 2D geometric model

to digital instruments, making it possible to achieve greater integration of heterogeneous data between different systems and, ultimately, better and more cognitively complete results. Creating 2D (Fig. 4) and 3D models[17] (Fig. 5) makes it possible to shift from a real object to its

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[17] 3D models by: Francesco Borgogni, Alekos Diacodimitri, Giulia Pettoello, Luca J. Senatore. 2D models by: Martina

representation by selecting some of the endless data regarding the object (Lo Brutto, M.L. & Meli, P., 2012; Brusaporci, S., 2015).

Two issues have to be tackled when the moment comes to build models and execute drawings of extremely irregular artefacts such as the theatres in this study. The first involves the need to understand and underscore the unique aspects of the contexts in question - large, sprawling areas and geometrically irregular archaeological artefacts - since the latter effectively stop the surveyor from identifying sharp edges or precise forms. The second issue involves the representation scale, in the case of 2D models, and the level of detail for 3D models.

The process used to define the general and detailed 3D models from point clouds is divided into separate phases that follow on from the registration of the point clouds and allow accurate determination of the topology of the surfaces. One key moment is the editing of the point cloud; this involves eliminating all unnecessary data and importing it into processing software[18]. The second phase (the topological study) is basically aimed at reducing the number of points[19] and controlling the overall noise[20] of the model. The third phase (meshing) generates a polygonal surface[21] by using Delaunay's algorithm to interpolate the optimised point cloud. This procedure ensures a fairly reliable topological and metric model that the operator can control and improve by intervening on several parameters such as the measurement of the angle of adjacent polygons, the maximum length assigned to the edges, and the area of each single face. The last post-processing phase is tasked with not only correcting any problems that may still be present along the edges of the border[22] and the general polygonal surface[23], but also compensating the holes[24] in the model caused by lack of data in the initial points cloud.

Just in Jerash (Fig. 6) we decided to take another approach and create models not only from point cloud obtained by laser scans. We decided to use SfM to acquire several particularly interesting archaeological elements: an aedicule, the vaulted surfaces of the vomitoria and the scaenae frons of the theatre. The latter were then processed using Agisoft Photoscan software. Part of the study focused on the construction and analysis of the model of the vaulted surface (Fig. 7). All the models obtained, whether geometric, texturised or thematic[25], were the basis for a series of considerations about the form of the surfaces, their regularity/irregularity, state of conservation and analysis of the materials. To document the morphology of each theatre we were able to produce traditional 2D geometric and architectural representations[26].

Attenni, Carlo Bianchini, Francesco Borgogni, Eliana Capiato, Chiara Capocefalo, Alessandro Cappelletti, Francesco Cosentino, Paolo Di Pietro Martinelli, Alekos Diacodimitri, Mario Docci, Carlo Inglese, Alfonso Ippolito, Daniele Maiorino, Giulia Pettoello, Francesca Porfiri, Luca J. Senatore, Gaia Lisa Tacchi.

[18] Cyclone 9.1, Rapidform XOR, Geomagic Studio 10.

[19] Noise reduction: a command that compensates the error of the scanner by shifting the points to a more statistically correct position. The so-called noise phenomenon is defined as an increase of the uncertainty of each measurement, with an arrangement of the points that differs from the theoretical square grid established by the operator during acquisition. This condition is quite frequent and is due to environmental and physical interference with the instrument during scansion. During meshing this condition can generate non-existent contours and corners and edges.

[20] *Scans noise* is defined as an increase of the uncertainty of each measurement, with an arrangement of the points that differs from the theoretical square grid established by the operator during acquisition.

[21] Given a set of points *P*, this algorithm makes it possible to define a grid of triangles in a surface. The grid is such that, for every circumference circumscribed in a triangular face, no point of *P* (apart from those that form the triangle itself) lies inside the circumference.

[22] *Edge correction:* a command that modifies, mirrors, divides, shifts or eliminates edges (and therefore faces).

[23] *Polygon editing*: a command that can add or remove vertexes, eliminate unwanted intersections, invert the normal vectors, i.e., improve the surface and yet maintain the original geometry.

[24] Hole filling: a command that compensates the holes in the surface by inserting new vertexes, edges and faces using as reference the curvature around the area where data is lacking. The reference area is chosen by the operator.

[25] The geometric model has no chromatic or material data it is still very useful to study the arrangement of masses, geometry and proportions as well as understand the reciprocal position and relationship between the elements in the architectural composition.

Instead the texturised model helps to define the formal aspects and state of conservation of the artefact by first of all using the RGB data obtained from the digital images acquired by the same instrument at the same time as the laser scansion: the chromatic data in these images is very accurately linked to the geometric position of the surveyed points.

Finally the thematic model exploits the symbolic nature of colour to provide information about several different aspects. By using colour to establish homogeneous areas in the model we can highlight forms, the heterogeneity of the materials, their state of conservation and sometimes even their degradation pathologies.

[26] A geometric diagram tends towards geometrisation of the elements to be represented, explicitly indicating the

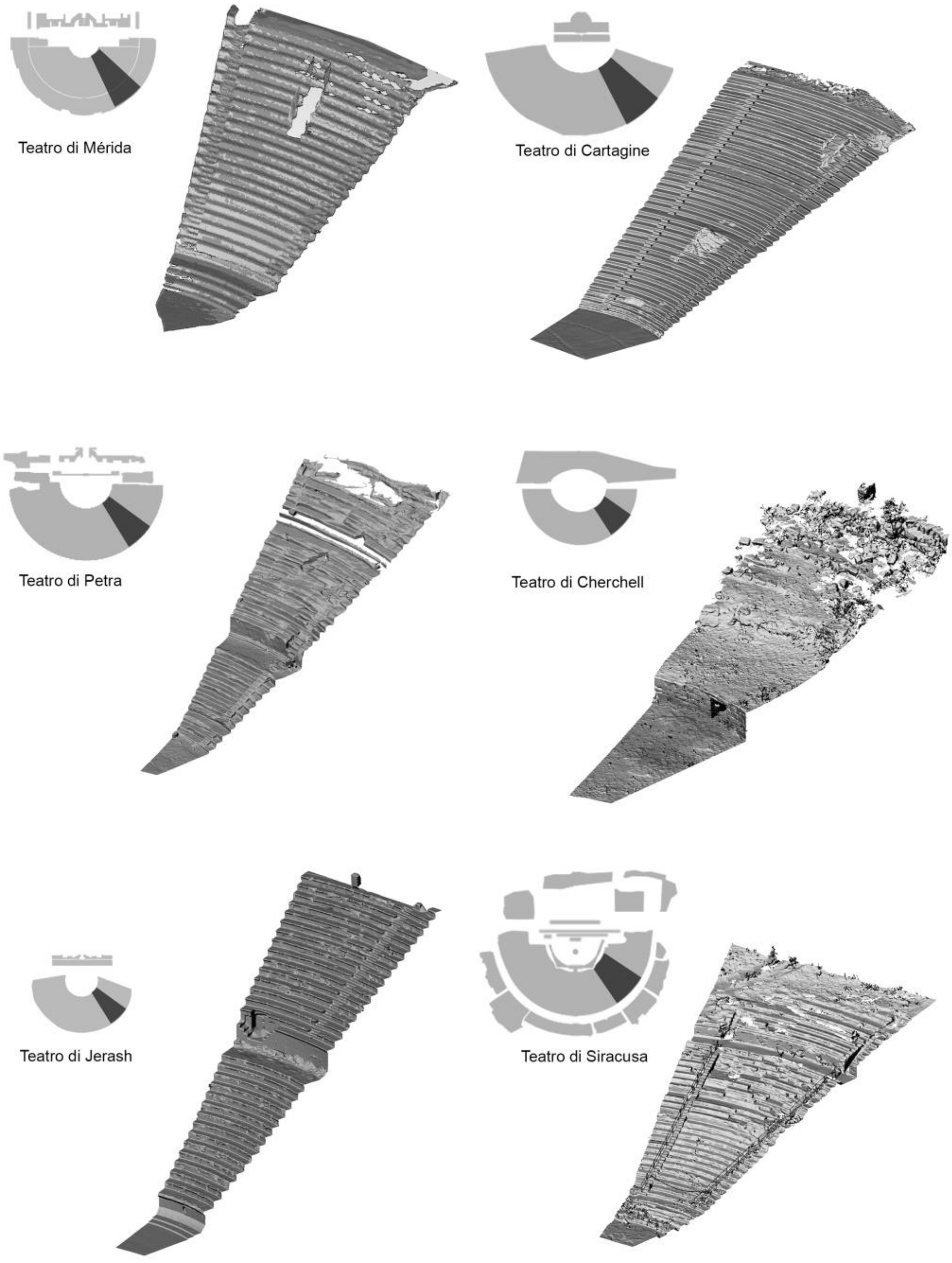

Fig. 5: Construction of a mesh model of part of the cavea of each theatre. The models offer a view of the results obtained by operation of editing and post-processing of numerical models

Choosing which drawings to produce depends on the objective to provide the most comprehensive cognitive picture of the six theatres. The plans show the relationships between the structure and

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morphology and spatiality of the artefact, an architectural diagram shows the real configuration of the elements and provides graphic characterisation, indicating the quality of the surfaces or their state of conservation.

Fig. 6: SfM: construction of details of elements in the theatre in Jerash: a vomitorium, an aedicule of the scaenae frons, a capital

its context, morphology and sequence of elements:the cavea, the scaenae frons and the tibunalia (where present), etc. The elevation profile was enhanced by creating a transversal section, while the longitudinal section boosted our understanding of the shape of the scaenae frons in the theatres where it is still present: Mérida, Petra and Jerash.

Instead, for the theatres in Carthage, Siracusa and Cherchell we decided to turn the section towards the cavea, providing data about the treatment of the surfaces and state of conservation of the materials.

Any model is the end product of the discretisation, interpretation and registration of certain parameters (metric, angular, colour, etc.) made by an operator or by a device that explores the object and isolates individual points. Given the problems we had to collect data only by visualising the cloud in parallel projection, to complete the architectural representation we occasionally chose to superimpose orthophotos on the geometric representations. These highly photorealistic orthophotos enabled us to integrate simple geometric restitutions and improve our knowledge of the artefacts. Another important aspect was the possibility to visualise, explore and export images of the cloud in which some points are recoloured from blue to red depending on reflectance values. In fact, chromatic differences allow a point-by-point interpretation of the material characteristics of the analysed objects. The operator can use this data either to acquire better knowledge during processing, or to provide a more comprehensive communication.

IT devices do have much greater potential due to the continuous technological progress made in the field of survey and everything associated with the restitution of drawings. Firstly, digital graphic models can be represented within vast virtual space without a reduction of scale vis-à-vis reality; secondly, they are not bound to any specific, previously-chosen representation method (perspective, axonometric projection, orthogonal projection, etc.), but reacquire real three-dimensionality inside the computer that provides several simultaneous, real-time visualisations of the same object.

5. *Data Analysis*

Data acquisition and processing does not end with the creation of 2D and 3D models, but rather with the drafting of hypotheses based on the interpretation of those models. The aim of our study was to interpret scientifically the six archaeological complexes. To achieve our goal, we

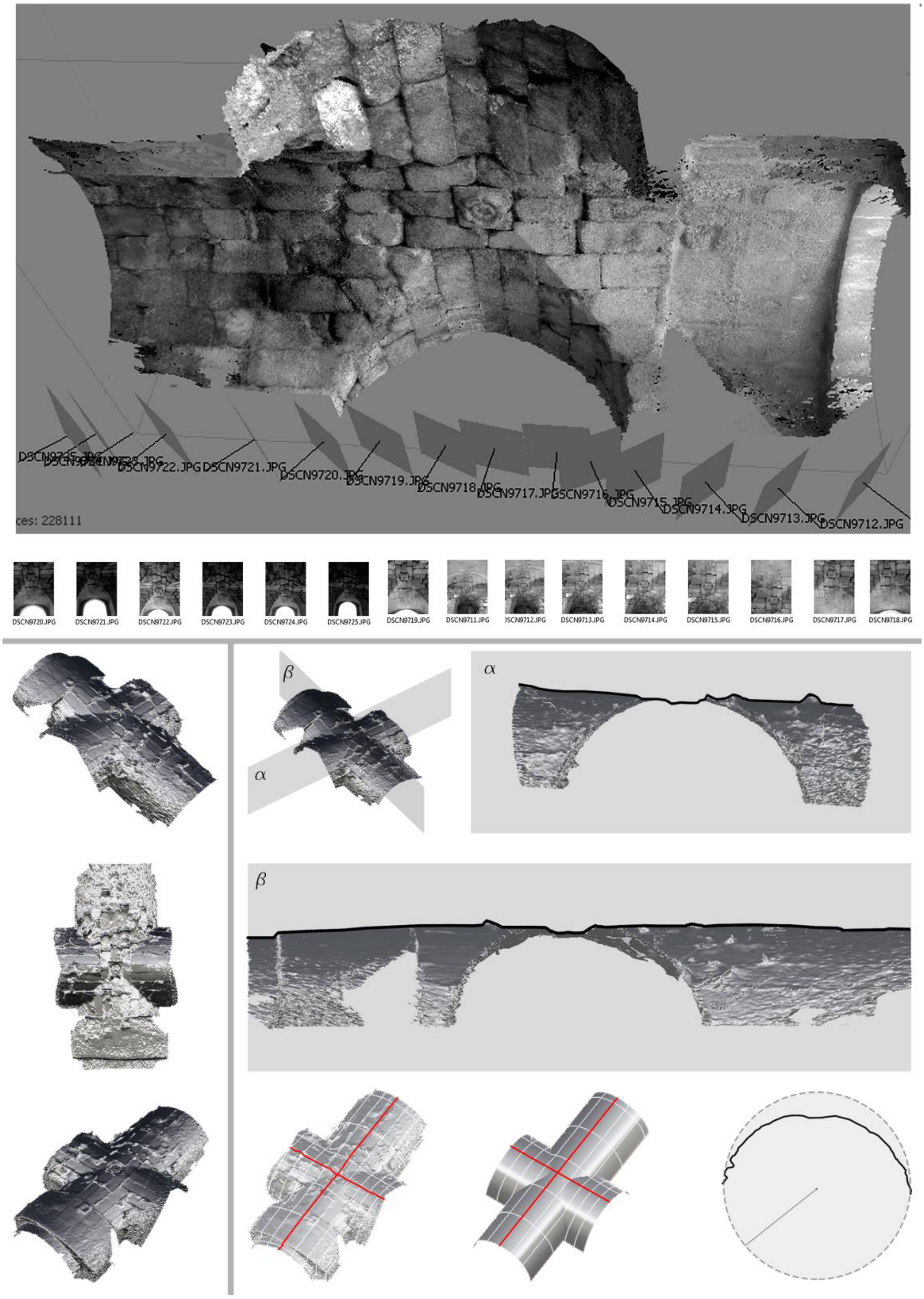

Fig. 7: Analysis of the intrados of the rib vault. Sections of the polygonal model and geometric analysis: comparison between the generatrixes and directrixes extracted from the real model and construction of the ideal model.

used a consolidated method allowing us to not only examine each theatre individually, but also compare them based on what they had in common. Obviously our considerations had to be based on reliable data that can only be provided by a scientifically correct approach, one which we duly used during data acquisition and processing.

The drawings, based on data obtained by integrating several non-contact survey methods, allowed us to propose several hypotheses initially based on a critical morphological and typological analysis and then on our measurements.

The analysis of the form and geometry of the theatres was operatively turned into a search for a basic building/proportional module by merging the formal study with the measurement study. We wished to either prove or disprove the existence of a geometric design matrix and a reference module by examining the overall structure of the theatres, identifying the building solutions and, where present, their decorative elements (Salvatore, M., 2007 ; Centofanti, M., 2008).

We checked also the geometry and dimensions of the layouts of the theatres based on the essays of two important treatise writers both involved with theatrical buildings, albeit each in his own way: the De Mensuris and Stereometrica by the mathematician Heron of Alexandria (first, second or third century A.D.?) and De Architectura by the Latin architect Marcus Vitruvius Pollio (first century B.C.) (Bianchini, C. & Fantini, F., 2015).

The results are illustrated in the 2D and 3D models; they confirm the importance of a cognisant use of hi-tech instruments to acquire and communicate information.

5.1 Comparative analysis: correspondence with the Vitruvian rule

In *De Architectura* Vitruvius indicates the parts and elements that make up a Roman theatre; he describes the main geometric constructions and rules required to build them (Book V). The latter can be divided into three main groups: the configuration of the cavea and its ratio with the theatre stage; the proportions of the theatre stage; the proportions and composition of the wall behind the theatre stage. Vitruvius' description explains the criteria that need to be followed in order to build correctly according to his canons for the Roman theatre (Fig. 8).

Vitruvius indicates the best direction the theatre should face and establishes certain key elements. The site has to be a salubrious area in a good position, but not facing southward since the sun would flood the theatre and air would not be able to circulate; as a result there would be a reduction in the moisture in people's bodies. He suggests avoiding places with bad air; he also says that the theatre should be placed in such a way that the spectators do not have the sun in their eyes. He states that if these rules are followed then the acoustics and usefulness of the theatre will improve. Most of the new theatres followed his suggestions and were built facing north (Gros, 1997).

5.2 Comparative analysis: Heron's theory

In his *De Mensuris* 24, 'Measurements of Theatres', Heron writes: "We can measure a theatre in the following manner: if the major perimeter of the theatre is 100 feet and the minor perimeter is 40 feet, we know how many people it will be able to contain. Calculate as follows: the major perimeter added to the minor perimeter is equal to 100 + 40 = 140 feet, 1/2 x 140 = 70 feet. If you count the steps of the theatre you will see there are 100; 100 x 70 = 7000 feet; this is the number of people the theatre can accommodate, 7000".

In paragraph 42 of Stereometrica (40-43) entitled "Different ways to calculate the catini", Heron provides other examples of how to calculate the seating capacity of a theatre: "A theatre with an outer circumference of 420 feet and an inner circumference of 180 has 280 rows of seats; to determine the seating capacity proceed as follows: the outer circumference, plus the inner circumference is equal to 420 + 180 = 600 feet; 600/2 = 300; multiple 300 by the number of rows (280) gives 300 x 280 = 84,000 spectators; because each foot corresponds to a person. If the total is 600 feet, divided it by two, to obtain a half: 1/2 x 600 = 300. If there are 50 rows: 50 x 300 = 15,000 feet. This is the number of people who can enter the theatre because the space of one person is equal to the width of a foot".

In paragraph 43 he illustrates another two examples of how to measure the seating capacity of theatres: "In another theatre with 250 steps, the first row accommodates 40 individuals, the last row 120 individuals; to calculate the total number of individuals proceed as follows: add the

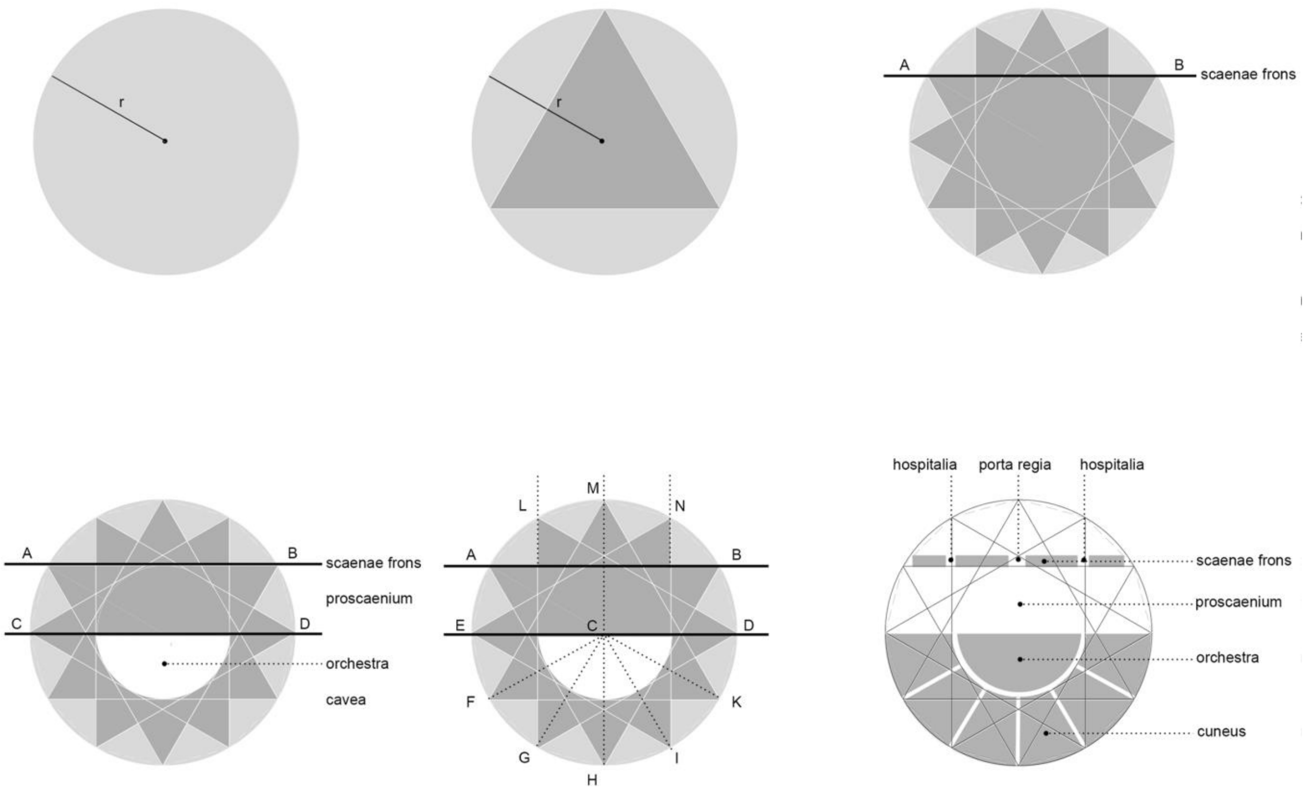

Fig. 8: The Vitruvian construction of a Roman theatre

first step to the last step, i.e., 160 individuals and divide by two: 160/2 = 80; 80 x 250 = 20,000 individuals: this is the seating capacity of the theatre".

In this study we made a comparison between Heron's theory and several theatres. We used a previous study of the theatres in Petra, Jerash and Mérida considering that the state of conservation of the other theatres in Carthage, Siracusa and Cherchell did not allow us to determine the values of the cavea needed for verification (Fig. 9).

Mérida

According to Heron's rule, the intermediate semicircumference is (421+124)/2=268 pedes. The *analemmata* is 52 pedes. The width of the seats is 2.5 pedes, so the theoretical number of rows is 21 and the number of spectators is therefore 268 x 21=5,681 *loca*[27].

Petra

According to Heron's rule, the intermediate semicircumference is (359+130)/2=244 feet. The *analemmata* is 79 pedes. The width of the seats is 2.3 pedes, therefore: 79/2,3=34 rows, and the number of spectators: 244 x 34=8,380 *loca*.

Jerash

According to Heron's rule, the intermediate semicircumference is (317+107)/2=139 pedes. The *analemmata* is made up of 8 modules of 8 pedes (64 pedes). The width of the seats is 2

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[27] The seating capacity of the cavea is unanimously acknowledged as a crucial datum for the dimensioning of the theatre; another hypothesis believed to be reliable is the hypothesis proposed by Christian Hüelsen who believed it was necessary to calculate a foot and a half, in other words roughly a 44 cm width per person. This hypothesis gives the following: the theatre in Minturno, 4,600 seats; the theatre in Venafro, roughly 5,000 seats; the theatre in Volterra, 2,000 seats; the theatre in Trieste, roughly 3,500 seats; the theatre in Fiesole, 3,000 seats; and the theatre in Cassino, roughly 2,000 seats.

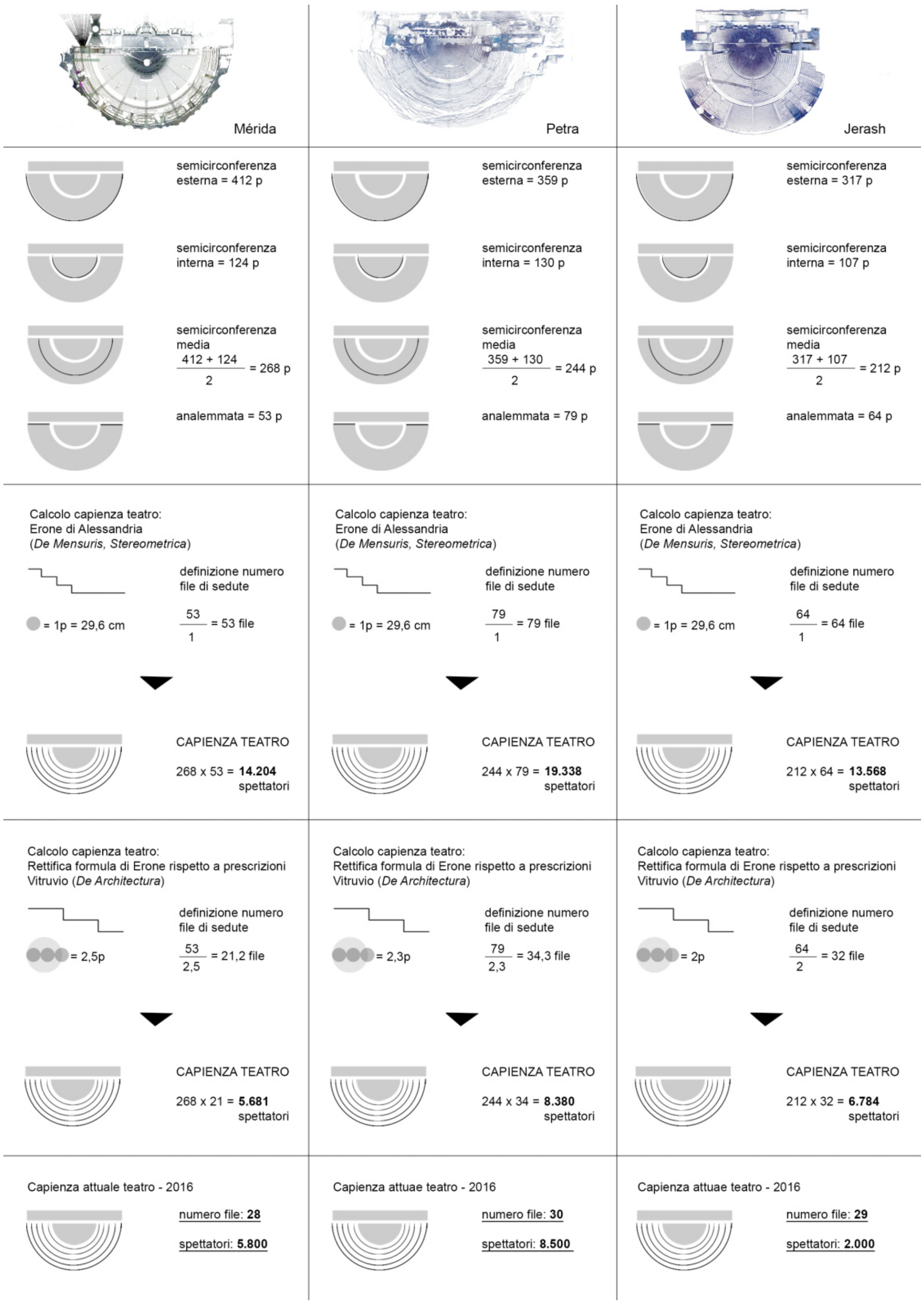

Fig. 9: Comparison between Heron's rule and the current seating capacity: the theatres in Mérida, Petra and Jerash

pedes, therefore the theoretical number of rows is 32; and the number of spectators 212x32=6,748 *loca*.

5.3 Metrological Analysis

Verification was performed for the theatres in Petra, Jerash and Mérida considering that the

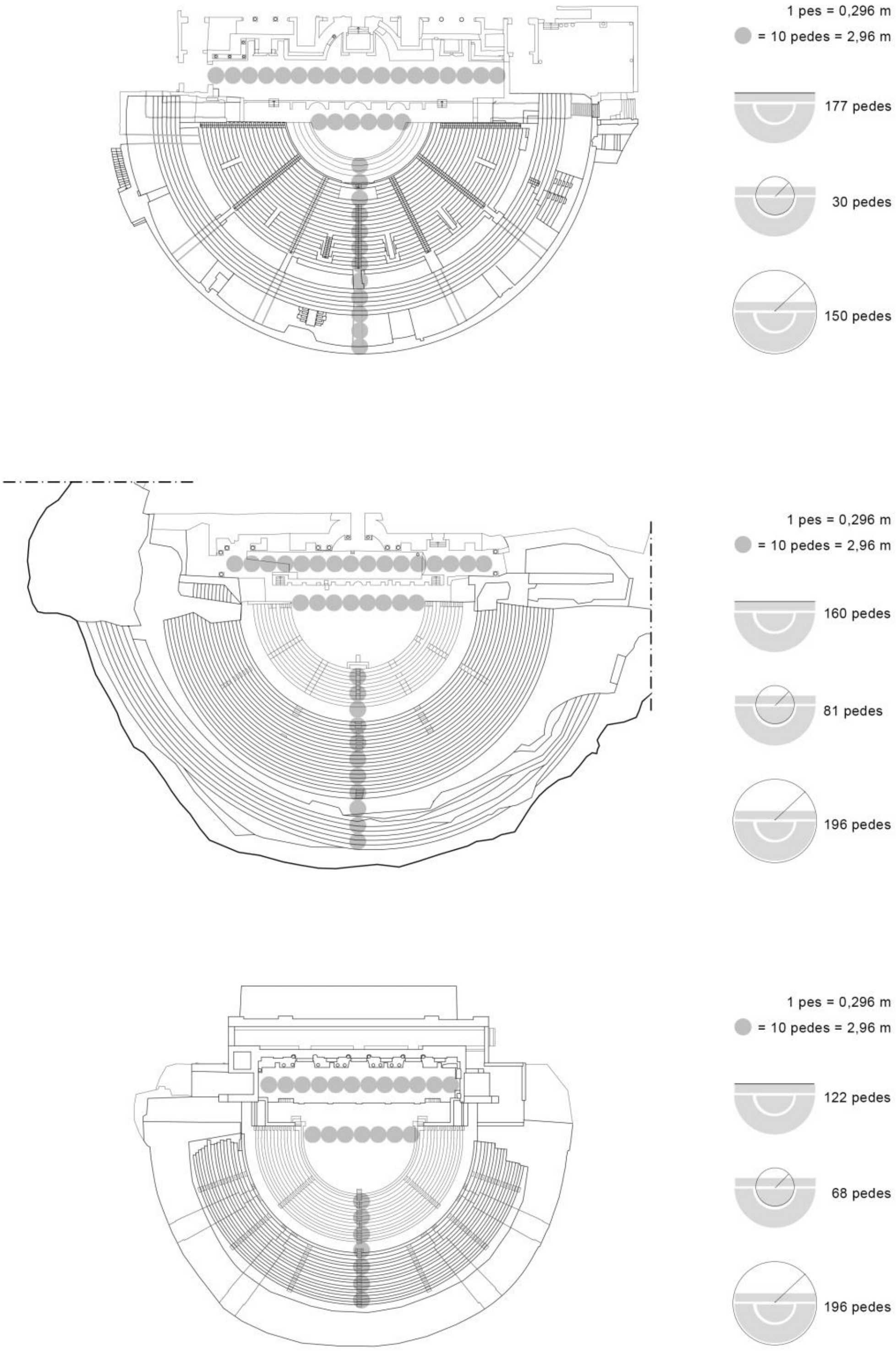

Fig. 10: Analysis of the measurements. Comparison between the theatres in Mérida, Petra and Jerash.

state of conservation of the theatres in Carthage, Siracusa and Cherchell did not allow us to determine the values needed for this procedure. Since the theatres were either built or restructured under the Romans, we took as our base module the Roman pes (with a value of 0.296 m) and its multiples, such as the pertica (equal to 10 pedes). The metrological analysis was performed on the main elements of the theatres: the diameter of the orchestra, the diameter of the cavea (adding together the summa, media and ima cavea) and the length of the theatre stage (Fig. 10).

Petra
Diameter of the orchestra 120 pedes (35,523 m)
Radius of the cavea 98 pedes (29,00 m)
Length of the theatre stage 81 pedes (23,97 m)

Jerash
Diameter of the orchestra 68 pedes (20,12 m)
Radius of the cavea 98 pedes (29,00 m)
Length of the theatre stage 122 pedes (36,11 m)

Mérida
Diameter of the orchestra 61 pedes (18,00 m)
Radius of the cavea 150 pedes (44,40 m)
Length of the theatre stage 177 pedes (52,39 m)

6. Conclusion

The main goal of any survey is to provide the most comprehensive cognitive picture of the artefact as possible and then communicate the results, i.e., a synthesis between interpretation of the data and the most objective restitution possible of said data. Generally speaking, this involves graphic, geometric and architectural drawings. Access to a wider range of contents makes it possible to produce new models and rethink the concepts of analysis, processing and communication of survey data within a much broader framework of integrated digital representation. In this context, 2D/3D representation is not the only way to illustrate *in-depth knowledge* or manage multiple models, i.e., the starting point of any dynamic interpretation of new information. This data is the basis on which to develop new analyses, performed to selectively study different aspects of the analysed objects. Specific methods can be used to communicate the ensuing results and filter the latter depending on the user to whom the information is intended, i.e., whether the person is a generic user or more or less highly specialised. This information can be the new starting point for further analyses, making it possible to examine the case studies from different angles; this corresponds perfectly to the now consolidated concept of survey as an open, dynamic knowledge system.

To understand and interpret the theatres we chiefly used 2D and 3D drawings highlighting the unique features and geometric, morphological and spatial characteristics of each theatre.

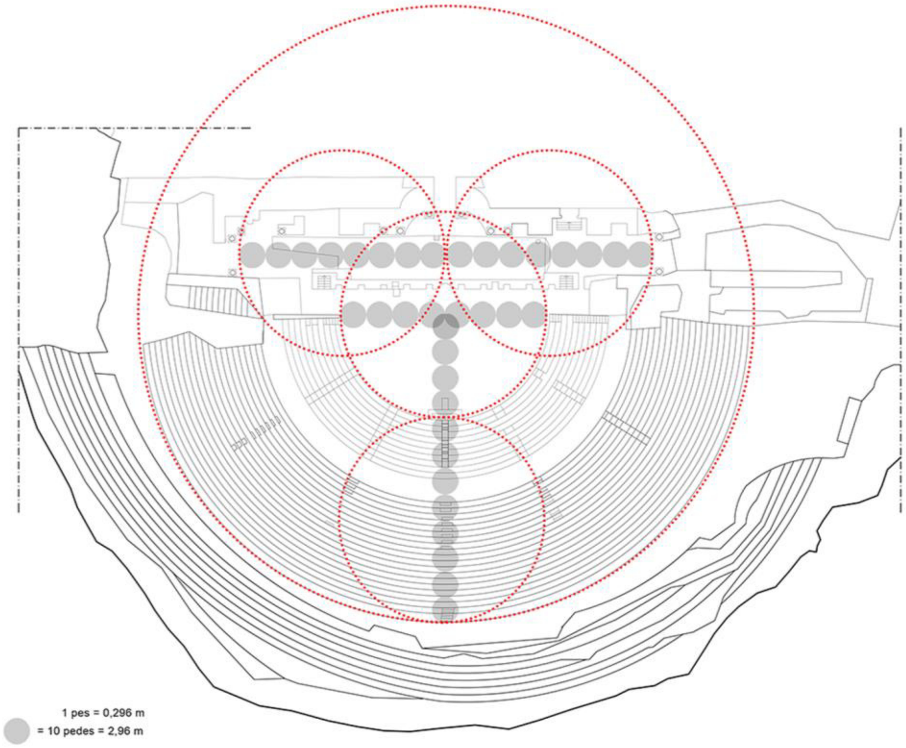

Fig. 11: Analysis of the measurements. The theatres at Petra.

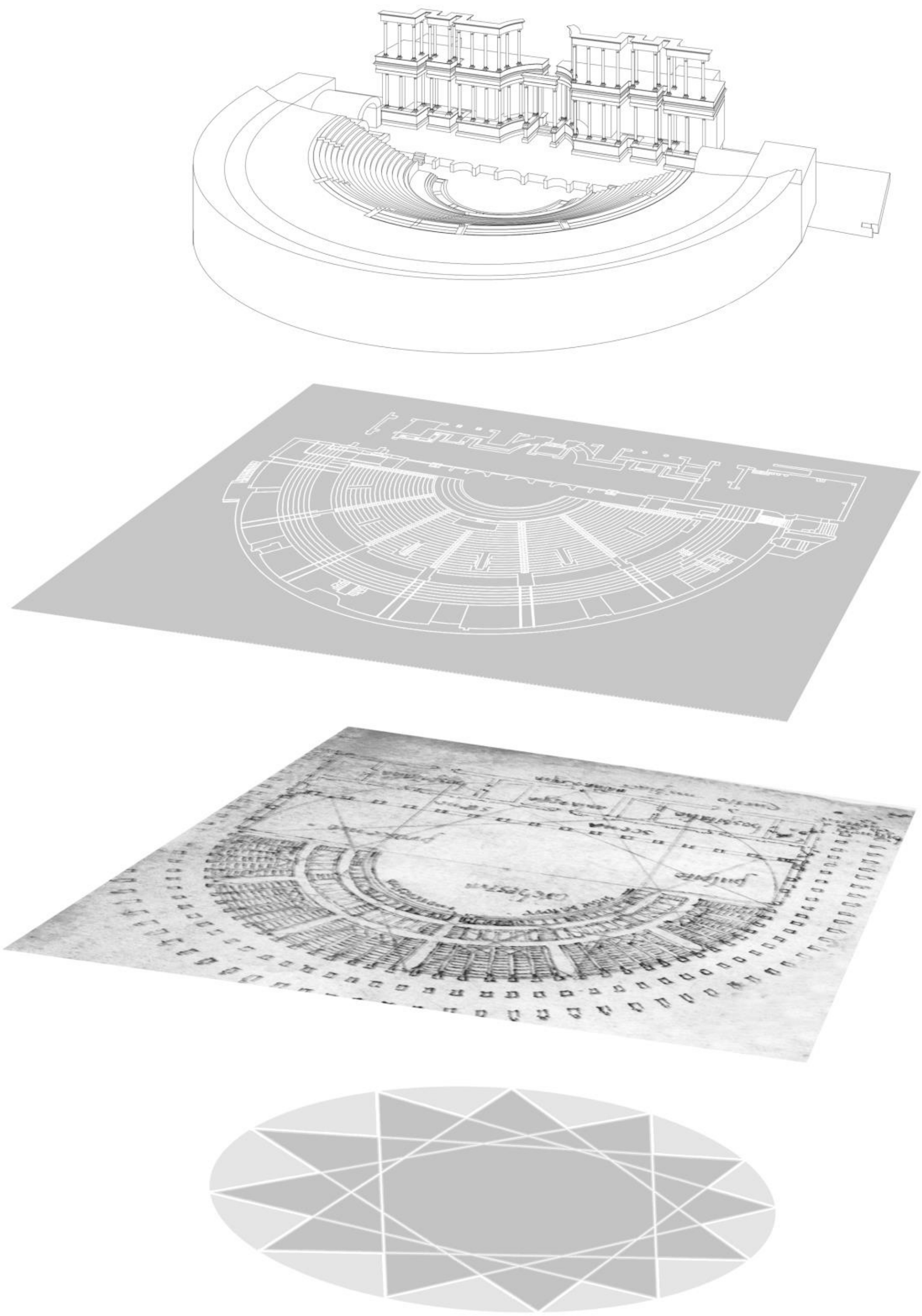

Fig. 12: The Vitruvius’ construction for roman theatre

Accordingly, geometric drawings, architectural drawings and thematic models, characterised by the restitution of different kinds of appropriately selected data, are very successful. In fact, often the selective, specialised interpretation of several features of an artefact can provide a comprehensive cognitive picture of the analysed objects.

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