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THE GREEK THEATRE OF SYRACUSE. FROM THE SURVEY TO THE PROJECT OF AN INNOVATIVE MICRO-LAMINATED WOOD CONSTRUCTION SYSTEM FOR THE FRUITION AND ACCESSIBILITY OF THE *CÀVEA*

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Abstract

The research is the result of multidisciplinary contributions, from surveying to digital fabrication. The focus of the research is the valorization and accessibility of the ancient Greek theatre of Syracuse through the use of an innovative construction system in micro-laminated wood for the equipment of the *càvea* whose components were produced using numerically controlled machine tools. The Greek theatre hosts an annual cycle of classical plays, organized by the *Istituto Nazionale Dramma Antico*. The paper presents a study of modern 3D digital documentation techniques for the survey of archaeological heritage, aimed in this specific case at the development of a 3D model to support the realization of the full-scale equipment prototype. The study not only identified the geometric and formal aspects, but also the missing parts of the *càvea*, making it possible to customize the prefabricated elements that make up the equipment system which can be dry-assembled.

Keywords

Micro-laminated wood; dry construction; architectural survey; TLS; UAS; Greek Theatre; Syracuse.

1. *Introduction*

In a region such as Sicily, so rich in history and archaeological sites, the protection, fruition and enhancement of historical archaeological heritage have always represented a challenge of strategic importance.

Since the action of protecting presupposes, as a priority, the knowledge of the property, consequently, whenever it is necessary to study cultural sites, special attention should be paid to the issue of conservation directed toward the enhancement of the property. This also induces an economic interest that, in an indirect way, contributes, as it is well known, to the preservation of cultural heritage. Artefacts of the past should, therefore, be reputed not as objects to be contemplated, but as promoters of new and current potential for enjoyment, true cultural resources and values for the community.

Actually, it is well-established that without a real awareness of the value of historic assets on the part of the public and of those who live near them, any enhancement project could lose its effectiveness and incisiveness.

Therefore, a sense of belonging must be aroused in all categories involved in order to activate a virtuous process.

The present research deals with the category of archaeological assets that maintain the potential for use within the scope of their original function: ancient architecture of performing arts, stone theatres, which due to their material-historical peculiarities present fragilities that need to be faced and respected. Architectures with a high landscape value for which the offer of a tourist-cultural fruition is largely consolidated.

In this context, any intervention should align with the goals of 'sustainable development,' addressing the three key pillars-environmental, social, and economic-outlined in the 2030 Agenda. The focus should be on leveraging existing resources to enhance efforts in protecting and preserving cultural heritage.

The concept of ‘sustainable development’ was elaborated in the late 1980s in the ‘Our Common

Future' Report of the World Commission on Environment and Development (Bruntland Commission). The term 'sustainability' was here intended as a developmentalist approach, and the compatibility between the protection of ecosystems and socio-economic development was emphasized. (Davico, Mela, & Staricco, 2009).

In this regard, as early as 1972 in Stockholm for the first time the United Nations celebrated an international conference on the subject of the human environment by formulating the "United Nations Declaration on the Human Environment" in which human beings are considered both creatures and creators of their own environment.

The semantic shift from the 1972 "human environment" to "sustainable development" stems from a kind of reconciliation of environmental and social equity motivations with those based on the concept of development in economic terms. The purpose, then, is to be able to put in place strategic actions that provide for both environmental protection (broadly understood) and socio-economic development. Actions that, from the perspective of the scholar community, must be based on scientifically validated cognitive processes to have a positive impact.

Indeed, the conscious reading of the information drawn from the signs traced in the researched site is functional for knowledge aimed at enhancing them.

In particular, with regard to ancient theatrical architecture, as early as 1997, the Verona Charter stipulated that "whatever type of event is chosen, it is imperative that the fragility of the sites is respected and that the performances can contribute to enhancing the heritage and arousing the interest of spectators in the historic site in which they are set. A balance must be struck between the need for monument protection and the expectations of spectators, visitors and local residents. Systematic consultation will have to be practiced between the communities that own the sites, those responsible for conservation and the organizers of the performances".

On the basis of these cultural premises, the research[1] was aimed at the development of a specific research methodology in which the management information and the geometric-formal information of the Greek theatre of Syracuse (Fig. 1) produced thematic digital scenarios on which the development of a construction system, up to full-scale prototyping, of the new equipment of the *càvea* was based[2].

Fig. 1: Greek theatre of Syracuse: aerial view

2. Stone Theatre Architecture: Protection and Use

In Italy, the use of archaeological structures for theatrical activities became evident at the beginning of the 20th century.

The first ancient theatre to host again a classical performance was the Roman Theatre in Fiesole with the staging of Sophocles' tragedy "Oedipus the King" on 20 April 1911. On this occasion, the dilapidated or missing tiers of seats were reconstructed with wooden structures (Dei, 2021).

These first examples led to a gradual increase in the organisation of cultural events in Greek and Roman theatres and amphitheatres[3].

These are ancient structures whose use must be carefully planned, with the contribution of multidisciplinary expertise, and "calibrated on the specificities of individual monumental realities"

[1] The research is the result of the collaboration between the *Istituto Nazionale Dramma Antico* (INDA) of Syracuse, the Archaeological and Landscape Park of Syracuse, Eloro, Villa del Tellaro and Akrai and the University of Catania, sanctioned by the memorandum of understanding signed between the parties in 2021 concerning the: "Techniques and methodologies for surveying the Ancient Theatre of Syracuse and the development of an innovative system for equipping the *càvea* of the Ancient Theatre".

[2] The research was developed with the support of the *Environmental Design Laboratory* and the *Laboratory of Representation* the University of Catania.

[3] The cultural initiative to revive the classical repertoire of tragedies and comedies in its 'natural setting,' the ancient Greek Theatre of Syracuse, was conceived by Count Mario Tommaso Gargallo of Syracuse. In 1913, he formed a promotional committee that led to the creation of the National Institute of Ancient Drama (INDA).

(Department of Cultural Heritage and Sicilian Identity, D.D.G. n. 827, 15 April 2010).

Actually, many documents concerning the protection and safeguard of the archaeological heritage have been drawn up, among them the "Convention for the Protection of the European Architectural Heritage", Granada 1985, the "European Convention for the Protection of the Archaeological Heritage", Malta 1992, the 1995 "Segesta Declaration", the already mentioned "Charter of Verona" in 1997 "on the use of ancient performing arts venues", the "Declaration of Palermo on cultural heritage and interregional partnership in the Mediterranean", 2003, and the "Charter of Syracuse for the conservation, enjoyment and management of theatrical architecture" presented in Segesta, the result of a synergic work between national and international institutions which started in Syracuse in October 2004. The latter was implemented in the abovementioned guideline directive of the Department of Cultural Heritage and Sicilian Identity of 2010 with the purpose of providing the first effective tools for an "active protection" of places whose specificity in the archaeological panorama is particular "combining in themselves the function of open-air museums and buildings whose intended use since their construction still remains" (D.D.G. n. 827 of 15 April 2010 p.7).

In this process of conservation and fruition, a decisive role is taken by the formation of "cognitive dossiers on individual theatres and specific environments". In this perspective, one of the investigation processes is entrusted to a thorough and accurate survey, conducted with non-invasive operations, aimed at the restitution and recognition of the constructive structures, the identification of gaps and absences, for a full and objective restitution of the architectural artefact.

2D and 3D survey ensures the sustainability of the documentation and visualisation results over time according to the aims of the 2006 “London Charter for the computer-based visualisation of cultural heritage”. It lays down strict methodological principles so that the communication of cultural heritage through modern tools derives from a technical and intellectual rigour capable of providing scientific authority based on strategies of accessibility and sustainability.

Also, the use of technological instruments must be balanced with the objectives, principles and the willingness of the institutions in charge of the protection, conservation and enjoyment of the property to grant authorisations for surveying operations according to the planned interventions.

The cognitive process, implemented in the research, has produced an initial database on the state of the monument, comparable and compatible with any subsequent survey conducted "using the potential inherent in this technology (three-dimensional laser scanner), in the creation of three-dimensional models with a high degree of precision" (Charter of Syracuse, 2004).

Lastly, in order to identify effective strategies for the sustainability of theatrical use, in accordance with what has been promoted since 1914 with the staging of the first classical plays, the research tackled the issue of the equipment of the *càvea* of the Greek theatre of Syracuse, based on the dictates of the 1997 Verona Charter on the use of ancient places of entertainment, which stated that "in the case of organisation of performances, the equipment used should as little as possible harm the legibility of the monument and the understanding of its historical significance".

The purpose of the research is to contribute a methodological approach to the issue of the sustainability of fruition in relation to performing arts activities, in continuity with their ancient and original function.

The cooperative relations that, on the occasion of this study, have been established between the preservation authorities, INDA and the world of research mark a path of cultural development that impacts primarily on the human environment that hosts the architectural artefact being tested.

In fact, the dissemination of knowledge and results of the methodological process entails the sharing of questions, choices and solutions on the sustainable development of ancient theatres, functional to the formation of a scientific, technological and cultural system of planning that can also be adopted on sites other than the proposed case study.

2.1 The greek theatre of Syracuse: the point view of Archaeological Supertintendency

Since 1914, in the Greek theatre in the Neapolis of Syracuse, the National Institute of Ancient Drama has been staging the texts of ancient Greek tragedies, a theatrical genre that had a social and religious significance for the inhabitants of 5th-century BC Greece.

The theatrical text was, in fact, conceived as a dramatic extension of ancient rituals: the myth-tale was represented by real characters distinguished by their own psychological dimension.

Through Aeschylus' Sophocles' Euripides' works spectators experience in the Greek Neapolis ancient emotions on a journey through time.

The mediator of this journey is the ancient theatre of Syracuse, an extraordinary theatre built in the 5th century BC, which after more than 2,500 years still expresses all its power, beauty and "functionality".

The theatre, located on the southern slopes of the Temenite hill, can hold more than 15,000 spectators, however, during performances its capacity is limited to about 3,000 spectators, for precautionary reasons related to the reduction of anthropic pressure on the monument.

The theatre went through a long phase of oblivion, neglect and spoliation, especially the high *càvea* and the stage building, by the Spaniards of Charles V in order to build fortifications around the island of Ortigia.

In the second half of the 16th century, the Marquis Pietro Gaetani di Sortino restored the ancient aqueduct that brought water to the top of the theatre. Works still visible which facilitated the installation of several mills on the upper *càvea* (the "millers' hut" at the top of the *càvea*) (Voza, 2007).

It was not until the 19th century that significant excavation campaigns were carried out by Saverio Landolina and Luigi Cavallari, activity continued with great commitment by Paolo Orsi and in the 20th century, up to the year 1988, by the campaign of Giuseppe Voza.

In 1914, the National Institute of Ancient Drama in Syracuse inaugurated the cycle of annual performances, staging Aeschylus' Agamemnon. The First World War marked a period of interruption until 1921, when the performances resumed with Aeschylus' Coephoras.

Since 1914, the performances have represented a major cultural event in Syracuse attracting thousands of enthusiasts and scholars of Greek culture.

Setting up a temporary facility for the enjoyment of the *càvea* of the Greek theatre of Syracuse required the resolution of complex issues already stated in the "Charter of Syracuse" reiterated and expanded upon by the Archaeological Superintendency of Syracuse, which performed the role of high surveillance.

Many prescriptions have guided the development of research. Some of them include the following:

- mechanical lifting systems cannot be used: suspended loads are not allowed;
- nails cannot be used between connection systems: hammering is not allowed;
- the elements of the rigging equipment must be fireproof;
- an adequate ventilation chamber must be provided between the new rigging equipment and the *càvea* stone to prevent any possibility of interstitial dampness;
- at the points of contact between the rigging structure and the *càvea* stone steps, efficient protection systems must be provided to prevent any possible abrasion, scratch, etc;
- the installation overlapping the *càvea* must strictly follow the underlying geometry, which cannot be modified;
- the risers of the system should be unobstructed. This allows the underlying stone structure to be seen when observing the càvea from below;
- the load exerted by people must be well distributed. This avoids excessive stress concentrations on the stone.

The research involved a very long and complex preparatory phase, involving a 3D survey of the monument, from which the proportions and generative geometries of the *càvea* were derived.

A general "rule", a "generative algorithm", was then derived from the digital model.

3. The survey for sustainable fruition

With a focus on sustainable development, the analysis of the geo-anthropic environment, in relation to new and integrated possibilities of use, was conducted with a multiscale survey.

Integrated surveying, implemented through the concomitant use of several techniques and instruments, is fundamental for an in-depth and accurate restitution of the architectural reality and contemplates the production of updatable and implementable documents, proper to the process of critical knowledge, in compliance with the recommendations of D.D.G. n. 827 of 15 April 2010.

The degree of in-depth investigation chosen on the basis of specific criticalities encountered and conducted by steps, in certain parts of the theatre, also results in the production of documentation in digital format that can be easily consulted and analyzed, which is excellent for any monitoring investigations on specific vulnerabilities.

It is worth noticing in this regard that the previous surveys of the ancient theatre of Syracuse made available by INDA turned out not to be questionable on specific themes and not comparable with the data of the survey conducted on the occasion of the present research, therefore not suitable for the purposes of the Charter of Syracuse. It was therefore not possible to activate a comparative monitoring between the two surveys in order to provide answers to any changes the monument may have undergone over the years.

3.1 Data acquisition

Careful planning of survey operations, methods and equipment was required to produce a high-resolution 3D model.

There are many works in literature reporting the results of surveys carried out on theatres and amphitheaters using new digital systems (Nocerino, Menna, Remondino, & Saleri, 2013) (Erenoglu, Akcay, & Erenoglu, 2017) (Bilis, Kouimtzoglou, Magnisali, & Tokmakidis, 2017) (Barba, Barbarella, Di Benedetto, Fiani, & Limongiello, 2019) (Bassoli, Fallavollita, & Fuchs, 2022).

However, most of the analyzed cases concern existing theatres of which, unfortunately, only a few traces remain and for which modern technologies allow a virtual restoration. In the proposed research, however, the aim is to reproduce a virtual model that corresponds exactly to the real one whose main structure, fortunately, still remains.

This model will be the basis for the design of an ad hoc structure for the accommodation of viewers during the theatrical performances that will take place here. The aim is not to create a virtual reconstruction of the theatre as it was in its time, but to create a virtual model of the actual state in order to design a real technological system that can preserve what remains of this extraordinary architecture today.

At a time when there is great interest in the valorization, enjoyment and protection of cultural heritage, the decision to use new digital technologies for the acquisition and communication of information is essential when dealing with archaeological sites where historical events and natural phenomena have compromised their original configuration.

The choice of survey methods to be employed was influenced by the architectural characteristics of the site, its state of conservation and the ultimate goal.

The combined use of reality-based techniques (range-based and image-based techniques) is the most appropriate solution for the acquisition of metric and colorimetric information as it allows the limitations of each technique to be overcome: for example, if the laser scanner finds many shaded areas, drone aerophotogrammetry comes to the rescue.

In particular, the use of UAS (Unmanned Aerial System) platforms allows the unconventional survey of sites with a high level of documentation difficulty.

In fact, such instruments have been used for several years to survey cultural heritage. (Pepe, Alfio, Costantino, & Scaringi, 2022) (Papa & D'Auria, 2020) (Valenti & Paternò, 2021).

Aerial photographs can be taken in automatic or manual mode using cameras mounted on these aerial vehicles. Specifically, a Skyrobotic SR-SF6 hexacopter with a maximum take-off weight of 5.5kg (including payload) equipped with a 20.2 MP Sony QX100 camera and a DJI Spark quadricopter weighing less than 300g were used.

The former was used for nadir coverage and the latter for oblique coverage. The atmospheric lighting conditions were those of a sunny day.

The nadir images were acquired by three automatic flights, made possible by the GPS system integrated in the instrumentation and planned in the laboratory thanks to the SkyDirector software, which links the drone to the ground control station.

The flights, lasting 5-10 minutes each, were carried out at a constant altitude of 30 m above the lowest part of the theatre (take-off in the orchestra area), with overlap and sidelap values set at 65% (Fig.2).

On the other hand, with the quadricopter several flights were made in manual mode to capture oblique images at close range.

In this case, it was relied upon the pilot's experience to fly within sight, at a constant distance from the monument, and to take photos at 3-second intervals to ensure good overlap between images. The drone was kept hovering for each shot to avoid any blurring or shaking.

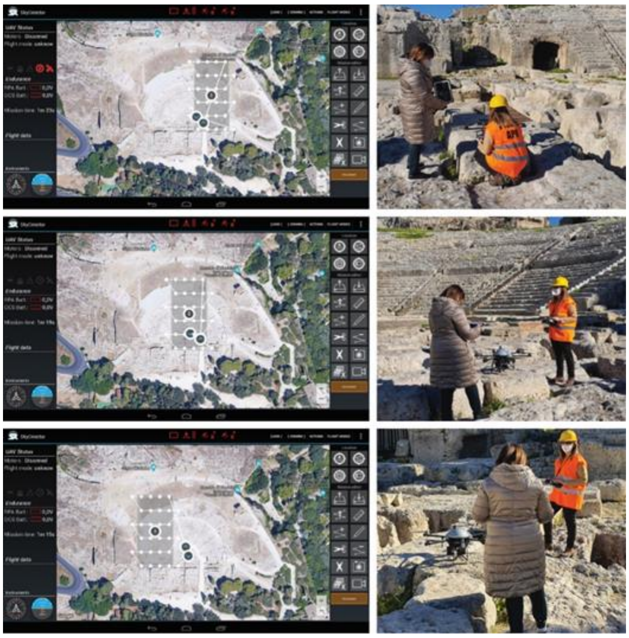

Fig. 2: Aerophotogrammetric survey from UAS

Flying in manual mode made it possible to take photos from different heights and perspectives, capturing details that are difficult to get in automatic flight.

Another fundamental factor referred to is the soil sampling parameter called "GSD" (Ground Sample Distance). This parameter represents the distance between the center of two consecutive pixels, essentially identifying the portion of soil contained within a pixel.

The GSD depends on the resolution of the camera on board the drone, on the focal length of its optics and on the flight height.

Since the lower the GSD value the greater the detail of the photograph in order to ensure a GSD value of no more than 1 cm/pixel, the flight height was kept around 10-20 m above the ground.

The basis of a well-executed aerophotogrammetric survey is the planning phase, which consists of a careful analysis of the site and evaluation of the most appropriate and physically feasible operational approach. Survey planning also includes the correct positioning of targets, both spatially and numerically.

The survey of the Greek Theatre in Syracuse used a variety of methods and instruments to produce a high-resolution 3D model. The survey, which implemented both the well-established Lidar technology and the most recent automated digital photogrammetry, took two days to complete. Specifically, on the first day, a UAS aerophotogrammetric survey and a single 360° phase difference scan were performed with the Faro CAM2 Focus 3DX130 laser scanner, positioning the instrument in the center of the orchestra. Before the work began, four 50x50 cm black and white fabric checkerboard targets were placed on the orchestra (the most visible area from several points of view).

Their position, expressed in three-dimensional coordinates, was obtained from the instrumental survey and was necessary to orient and scale the photogrammetric model.

On day two, the focus shifted towards one particular sector of the theatre (sector A), where more detailed virtual models were required as the prototype would be tested and designed. Three scans were taken with the Leica C10 time-of-flight laser scanner and additional oblique images were taken by UAS.

The integrated use of non-invasive digital techniques is particularly effective here, not only due to the possibility of obtaining a large amount of metric and colorimetric data within a short period of time, but also due to its ability in dealing with the restitution of models with a particularly complex geometry.

In this case, the scan resolution was kept high (one point every 5mm at a distance of 10m).

To facilitate the subsequent processing and alignment of the individual scans, a number of targets (4 magnetic and 14 checkerboard targets) were uniformly placed on the ground and on tripods and detected using semi-automatic procedures. The chosen resolution settings resulted in a scan time of approximately 30 minutes per scan.

3.2 Data processing

The survey operations allowed the restitution of two different dense point clouds, the first obtained from the TLS survey and the second obtained from the photogrammetric reconstruction of the images acquired by UAS equipment.

The data collected during the two survey campaigns were processed using specific software that required large computer resources.

In particular, the instrumental survey data were processed using Cyclone software, while the photogrammetric data were processed using 3DF Zephyr.

The latter software is based on the Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms and allows 3D reconstructions to be performed automatically.

In fact, when the user provides the software with a collection of images, the system automatically calibrates the cameras according to the information contained in the images, aligns them in 3D space and produces first a sparse point cloud, then a dense point cloud, then a continuous model (mesh) and finally a textured model (Fig.3).

In Structure from Motion processing, it is necessary to identify a series of clearly visible points in the photos, with known coordinates: these are targets, high-contrast elements with a clearly visible center, to be distributed over the surface to be surveyed. In the software targets are identified as GCPs (ground control points). The introduction of GCPs before any dense reconstruction is particularly important when working with different sensors and platforms. In fact, each SfM software requires a minimum of 3 GCPs to perform photogrammetric block adjustment, as well as scaling, rotation and positioning of the model.

A total of 352 photographs taken in the first survey and 354 taken in the second survey were used to create the 3D model of the monument.

The software offers a range of levels of detail (LOD) for 3D reconstructions. The level of detail affects the timing and point density of the point cloud. In particular, the photogrammetric point cloud of the entire theatre, obtained from the images taken during the first working day, was processed by setting the default setting and the category "nadir images". Then, thanks to the 4 targets set up during the survey operations, it was possible to import the point cloud from the laser scanner and to position the photogrammetric model on it using the command "Registration for control points".

After structuring the point cloud from the instrumental survey, the two clouds were merged in order to proceed with mesh generation. However, the large amount of data would have required considerable resources and processing time, so the merged point cloud was decimated before proceeding with the continuous model, by setting 1cm as the distance between one point and another.

Therefore, without damaging the quality of the results, a compromise was sought between some essential parameters and processing times.

The data obtained from the second working day were processed in the same way, resulting in a very dense final point cloud of sector A.

In this case, the data processing preset was set to “high detail”, which required long processing times.

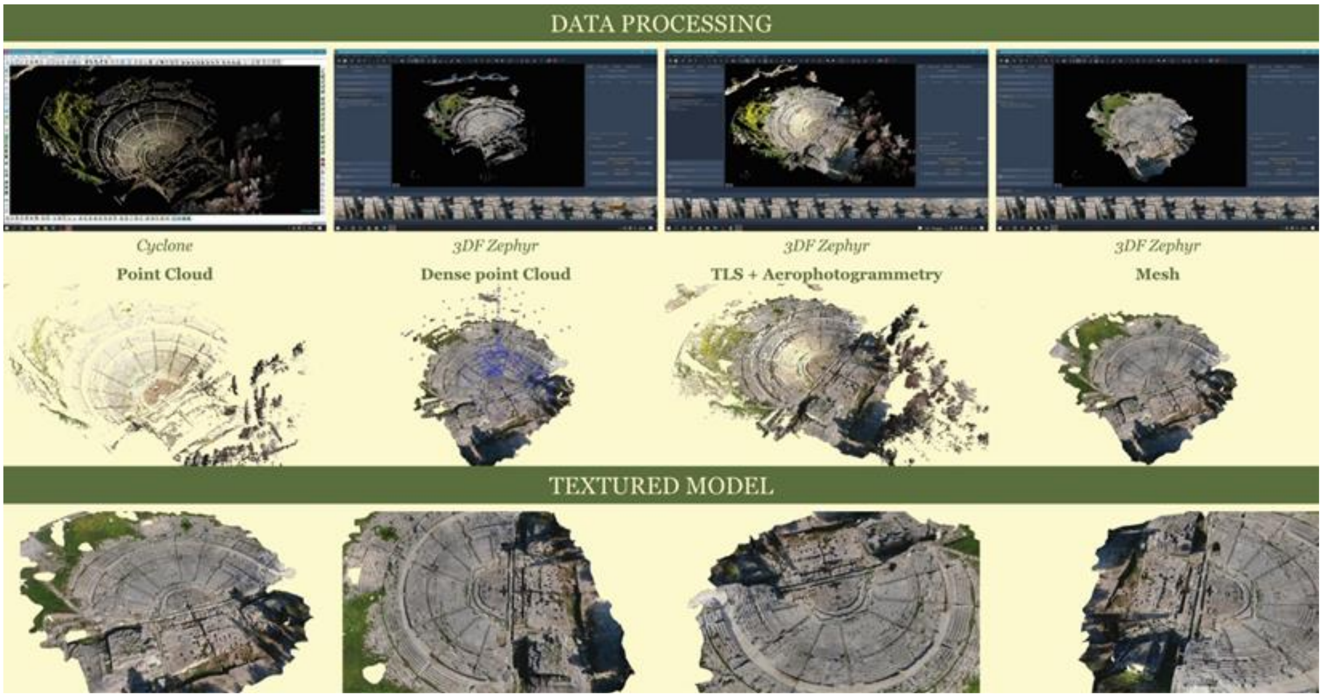

Fig. 3: Post-processing of the digital data: processing of the three-dimensional model

Again, point clouds from laser scanning and photogrammetry were combined to create a highly detailed 3D model.

A high level of detail in the geometric model was not sufficient to provide a realistic virtual representation, but at the same time good texture definition was essential. Finally, the two datasets (the model from the first survey campaign and the model from the second survey campaign) were merged into a single work environment. From the general model of the theatre, the orthophotos (plans, sections, elevations) were obtained in order to proceed with the production of the 2D drawings, while the 3D model of sector A was used to proceed with the design of the hypothesis of the seating construction. The long and detailed survey work was fundamental to the creation of an accurate 3D model. In addition, the metric and morphological data obtained from the surveys were used to develop a subsequent 3D CAD model of the of the structural details and the anchoring system for the moving parts.

Two digital representation methods were used: the polygonal and the mathematical. The first was used during the phase of surveying and developing the model of the theatre's condition, and the second during the phase of designing the technological part.

The procedures described in this paper are a test of the stages of a possible workflow that may also be applicable to other areas of the theatre.

3.3 *The 3D model for the design of the càvea's structural equipment*

The post-processing phase of the survey carried out with digital technologies is critical, especially when the architectural artefact is old and the material bears the signs of time.

The operator plays an important role in the restoration process, filtering the information from the "continuous" representation (orthophotos, perspective views) and transforming it into a. "discrete" 2D representation in CAD. It is at this stage that the correspondence between the graphical representation and the material reality is established. Traditional 2D representations of the theatre's *càvea* were created from the orthophotos, in particular the plan views and sections of the 3D model[4] (Fig.4).

Fig. 4: Orthophotos and 2D representations of the survey

Projective reasoning has allowed the verification of the genesis of the shape of the *càvea* through geometric analysis, in order to rediscover

[4] Thesis by Antonio Licciardello and Valeria Dilettuoso, entitled: *Equipment system for the càvea of the ancient theatre of Syracuse*, supervisors Prof. Luigi Alini, Prof. Rita Valenti, University of Catania, 2021.

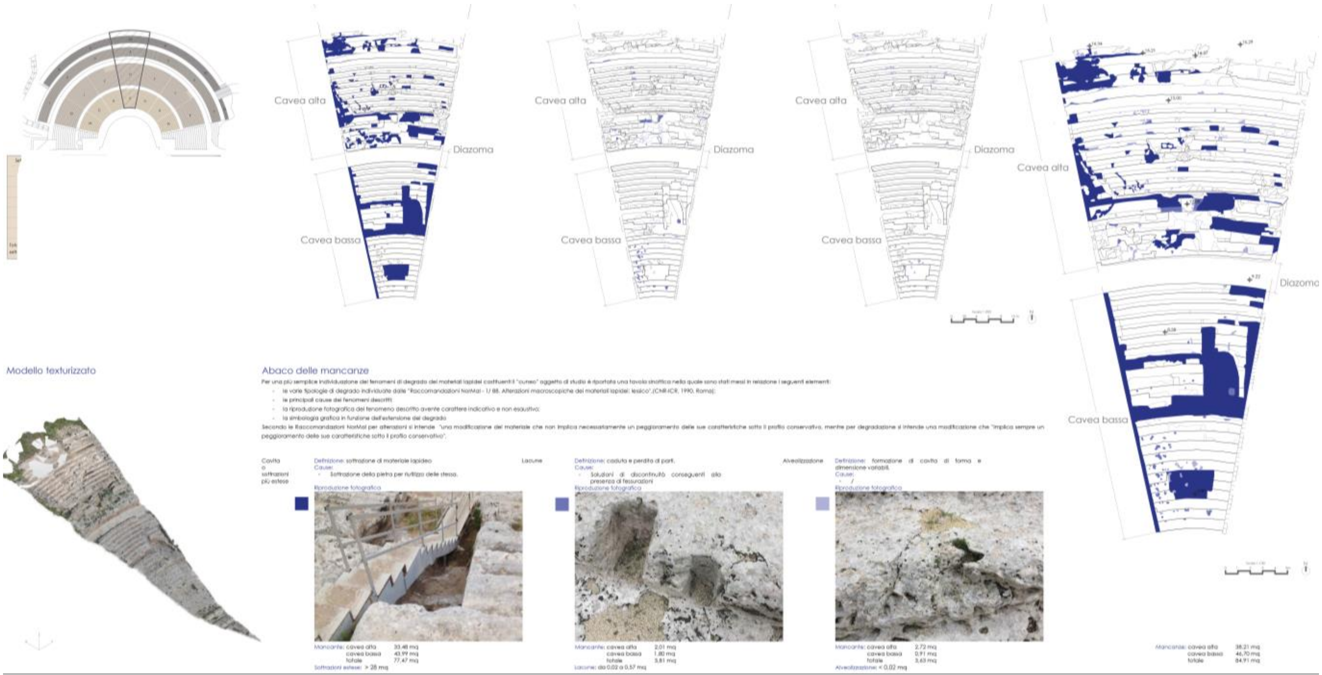

Fig. 5: 2D representations of the survey and radial cross-sections of sector A of the *càvea*

the "guidelines" for the design phase. Consequently, the basic construction system was defined, which bases its formal development on the geometry of the *càvea* derived from the precision survey.

The initial hypotheses considered a construction system with an annular layout, aimed at accommodating both the observed semicircular shape and the current assembly methods. However, the final solution adopted a system of load-bearing elements with radial development, which better aligns with the geometric design of the ancient theatre. The redesign of the radial sections, following the grid proposed during the design phase, was crucial in assessing the current state, particularly in relation to major gaps and material deficiencies (Fig. 5).

The 3D model of sector A, which reproduces the plan-altimetric articulation with a high level of detail, enabled the creation of all the radial sections (at a 1:20 scale), necessary for the executive design of the radial ribs and the system of support braces connecting the equipment to the current state of the *càvea* (Fig. 6).

Finally, the perspective views of the 3D model allowed an overall reading of the artefact, constituting an exact morphometric documentation, useful for the application phase of the research. These are the basis on which the digital mock-up of the tooling of the *càvea* in sector A was accurately developed and tested.

The sectional and perspective views with photo insertion allowed an initial virtual verification of the design choices, preparatory to the final phase of *in-situ* experimentation.

4. Application and digital manufacturing

Geometric rules guided the construction choices and manufacturing methodology of the equipment components. A number of alternative solutions were studied. Of the possible construction systems studied, that of micro-laminated wood met the requirements of safety, compatibility with the monument, speed of assembly, acoustic and visual comfort and fire protection. The next steps were a kind of “engineering” of an idea, which involved manufacturing the system components from wood panels using a CNC milling machine. All system components were made of STEICO LVL multilayer panels: multilayer made of glued spruce veneers, 22 mm thick. The panels used are CE certified, measure 220x300 cm and can be produced up to a length of 18.00 m. The choice of a small panel size, in addition to optimizing waste, meets the need to limit transport costs and allows the panels to be machined with widely used milling machines, also used by artisans.

Fig. 6: Digital model of càvea and insertion of the equipment

4.1 The càvea and the equipment system

The *càvea* is divided into 9 sectors, alternated by service staircases, each of them made up of 67 steps, mostly carved into the rock. The *càvea* is interrupted by a distribution ring, the *diazoma*, which separates the *summa càvea* from the *ima càvea*.

Equipping the theatre's *càvea* with an innovative system of temporary furnishings required long studies and surveying activities, the development of numerous prototypes at different scales, and numerous on-site tests which were carried out under the strict supervision of the Archaeological Superintendency of Syracuse and the Archaeological Park Management.

The research lasted about two years, during which period several survey campaigns were carried out and the prototypes developed were built and tested in the laboratory and on site, all carried out at the Environmental Design Laboratory of the University of Catania[5] .

The technologies used and the materials of the prototypes were validated by the Archaeological Superintendency of Syracuse.

Several laboratory tests were carried out on 1:5 and 1:3 scale models and 3 *in situ* tests were carried out on 1:1 scale model in order to compare the laboratory results with those obtained from the *in situ* activities (Fig. 7).

In a predictive way, on the basis of the available experimental data, the performance of the system was hypothesized by simulating the ageing process of the elements and their behavior in relation to different cycles of assembly, disassembly and reassembly of the same elements. The need for an off-site prefabricated construction system, produced with the aid of a numerically controlled milling machine, made up of micro-laminated, lightweight, small-sized, modular wood elements with interlocking wood-to-wood joints, introduced significant elements of innovation with respect to the rigging system traditionally used by INDA to equip the *càvea*. The latter is made up of 2.5 cm thick, 10.5 cm wide and 3 m long planks of fir wood, cut and shaped on site and fixed with metal joints (fully threaded screws and, in some cases, nails with improved adhesion): an artisan system typical of reinforced concrete carpentry applied to theatre equipment. It is no coincidence

Fig. 7: Test and *in-situ* assembly phases of the prototype

that the workers who would carry out the structural rigging have always been carpenters. The very high number of man-hours required for

[5] During the academic year 2022-2023, the student Giorgio Martorana contributed to the research conducted within the laboratory by submitting his dissertation.

the construction and dismantling of the structures will therefore imply long periods of inaccessibility of the site to visitors to the archaeological area. This is a highly critical element, in addition to the very low reuse rate (less than 30%) of the wooden elements.

The construction and dismantling time of the current system (March - July) is therefore one of the most critical issues highlighted by the Archaeological Superintendency and the Archaeological Park Management, which led us to opt for an off-site prefabrication system for all the elements of the new equipment. On the basis of a three-dimensional digital model, a tailor-made cladding for the *càvea* with a high technological and performance content was developed creating a product of high "industrial craftsmanship". The high performance of the micro-laminated wood used, from a structural point of view, in terms of fire behavior, slip resistance, comfort, compatibility and safety of the monument, etc., also meant a reduction in the total amount of wood used compared to the system currently in use. On the basis of the digital model of the *càvea*, a recurring module and geometry were identified for the *ima càvea* and one for the summa *càvea*. A separate discourse was carried out for the service stairs that separate the different sections of the *càvea* and for the *diazoma*.

Each module is made up of only four repeated modules (with slight variations in module geometry at the transition from the low to the high *càvea*).

The possibility of reducing the entire equipment system to a few elements is clearly an undeniable advantage, not only in terms of optimizing the production phases, but also in terms of simplifying and speeding up the assembly operations on site. Reducing the construction system to a few interchangeable elements also eliminates the need to stock spare parts. This makes it possible to renew the system every year with the few elements that need to be replaced. The components are assembled using a "push fit" method, which requires no special equipment for handling and lifting. An alphanumeric code is assigned to each component in the assembly diagram, aiding construction operations. Accelerating, standardising and simplifying the installation of the system has a clearly positive impact on the extension of the period during which visitors can enjoy the theatre, with consequent economic benefits for the Archaeological Park. The

Fig. 8: LAMM laboratory: CNC milling of the prototype components system equipment's.

decision to use wood-to-wood connections was based on a principle of caution against potentially damaging operations to the monument. As a result, a thorough study phase was required.

Determining the proper dimensional tolerance for the "half joints" while ensuring sufficient cohesion between the parts required an in-depth analysis of the geometric features of the joints.

This also involved examination of the thicknesses of the cutters used and their cutting specifications.

The transition from the digital design to the physical model required a complex evaluation of the "tolerance" allowed: the dimensional tolerance, the material used, the cutting carried out by the CNC (Fig. 8), the milling cutters used, and also the tolerance margin to be left for assembly operations on site.

To achieve this goal, a range of simulation and optimization techniques and software were utilized and contrasted throughout the development phase of the 1:1 scale prototype. Specifically, the RhinoCAM plug-in within the Rhinoceros software was used.

The component parts of the system are (Figg. 9, 10):

- ribs with variable geometry, 22 x 60 mm section, which make up the primary structure;

- laths of 22x40 mm section of three different lengths, which make up the secondary structure;
- top closing panel, trapezoidal in shape and 22 mm thick. The upper closing panel, in addition to configuring the seat top, stiffens the system by making all the structural elements work together;
- heel block.

The continuity between the ribs of the different steps is achieved with a “graft” joint involving the insertion of two wooden “pins”.

The protective interface between the wooden ribs and the theatre steps is resolved by a double layer of fireproof TNT, applied only to the treads of the steps. Where necessary, jute sacks filled with sand are used to compensate for minor unevenness in the stone steps. The ribs are distributed in a radial pattern at 40 cm intervals in the low *càvea*. In the high *càvea*, the number of ribs is increased in order to keep the distance between the ribs within 80 cm.

All components of the developed system are made of Laminated Veneer Lumber (LVL).

In this case, we are talking about panels that can be classified as wood-based products, "sheets" (veneers) of wood bonded with synthetic or natural glues that give the material homogeneous mechanical strength superior to that of the original wood.

4.2 Construction system and engineered wood

LVL is an “engineered wood” that falls into the category of structural materials. Panels are produced in various thicknesses (22 mm is the minimum thickness for structural use) and can also be produced in large sizes. The maximum product size is determined by the limits of the production plant (Menges, David Krieg, & Schwinn, 2016). This type of panel, in addition to a definable and certain structural performance, also has an excellent performance in terms of fire resistance and does not require any special treatment with

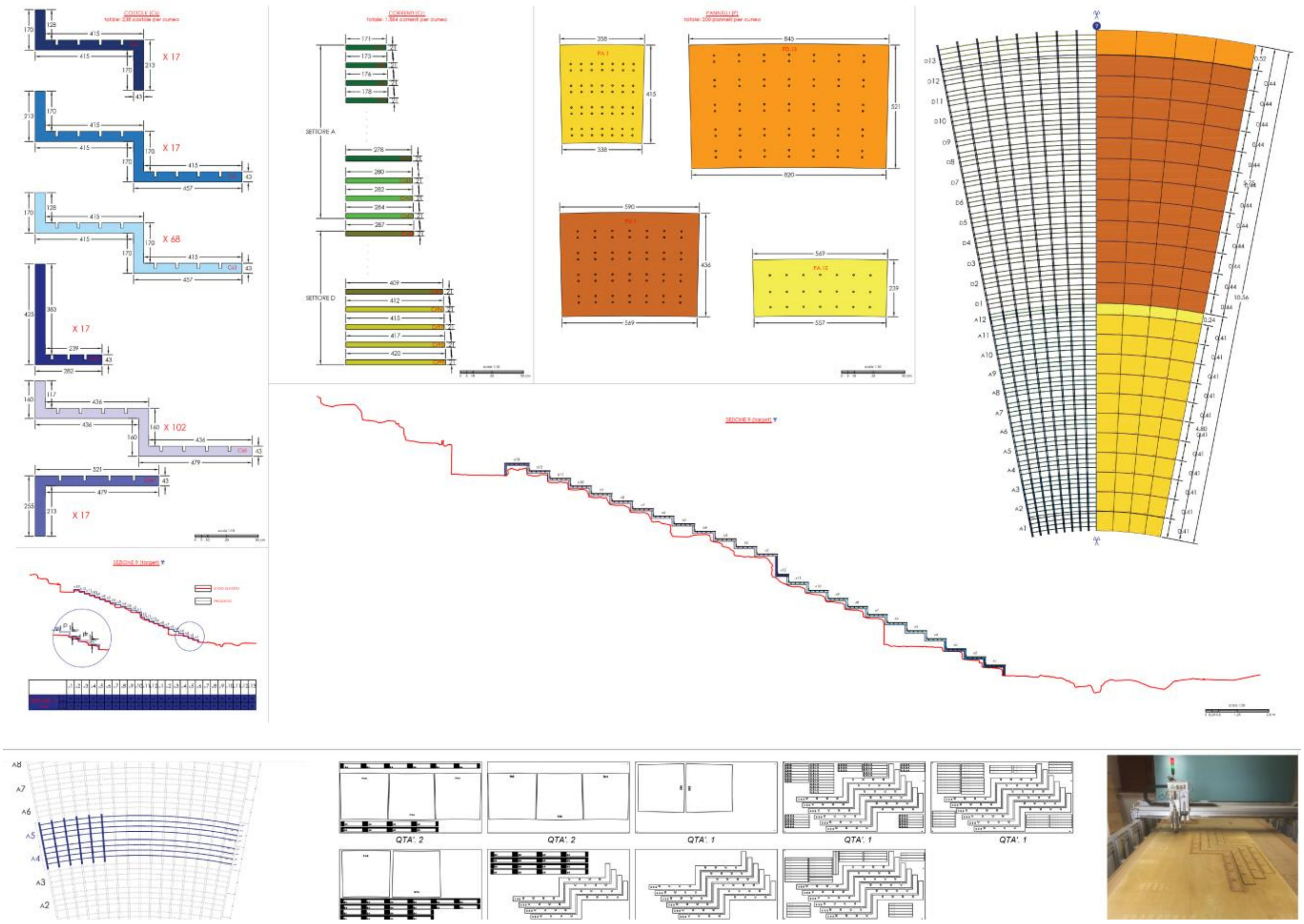

Fig. 9: Component schedule and panel cutting list

Fig. 10: Component schedule and panel cutting list

protective paints, and also has an excellent behavior with respect to exposure to atmospheric agents.

For these and other features in the development of the new equipment system, we collaborated with STEICO SpA, a leading manufacturer of micro-laminated wood panels, which supported us in the subsequent construction and *in situ* testing of the prototype.

The possibility of limiting thicknesses, of basing analyses on definable material data and behavior, of limiting the amount of waste material, and of using test species from fast-growing crops also brings clear benefits in terms (Dei, 2021)pine. These very thin "sheets" are then glued together. The raw material is largely sourced from sustainable forests, i.e., forests certified for sustainability and planned use of resources.

The log is "flaked" and reduced to "micro-lamellas" of 2-4mm thickness, which are graded by morphology and size after a quality check. After drying, which stabilizes the raw material, the "micro flakes" are glued by orienting the fibers in the longitudinal direction, then pressed and dried. One of the critical points of microlamellar's remains the use of synthetic glues, which, while making it possible to use small wood from fast-growing cultures, are at the same time a potential source of health hazards, especially in confined environments. As VOCs (Volatile Organic Compounds) disperse into the air, they can be harmful to the respiratory system. However, in the case of micro-laminated wood, the glues used are thermosetting and are not subject to changes due to variations in temperature and/or humidity. The durability of LVL elements for exterior use can also be further enhanced by surface treatment with impregnating paints, without affecting their excellent fire performance (Beorkrem, 2013).

5. Results and conclusions

The methodology applied in the research created a synergy between different scientific and cultural fields, opening up new possibilities of interdisciplinary collaboration. The survey resulted in a digital documentation of the monument, allowing its accurate knowledge to be functional for the development of compatible and sustainable interventions. In particular, the digitalization of the architectural survey has brought a number of advantages not only in terms of speed and accuracy of the survey and the 3D model resulting from the point cloud, but also in terms of the possibility of integrating the digital restitution data with the design and construction information inherent in the “Digital Fabrication” methodology (Volker, Michael, Thomas, Fabio, & Matthias, 2016).

The convergence between the two methods made it possible to monitor, step by step, the full correspondence between the complexity of the material reality (the *càvea* of the ancient theatre of Syracuse) and the design and manufacturing workflow of the equipment. The “Digital Surface Model” of the *càvea* obtained from the survey was the support for the verification, in a virtual environment, of the design choices based on the geometric results progressively refined during the definition process. The use of “Digital Fabrication” not only made it possible to create a site-specific construction system with a logic typical of industrial products, but also to evaluate assembly sequences by digitally simulating them. This possibility, particularly in the case of a monument of exceptional value, made it also possible to assess ex ante the possible criticalities associated with the manufacture, transport and assembly of the elements on site.

The digitalization of production processes has made it possible to optimize cutting operations, both in terms of speed and in terms of reducing waste and scrap.

Added to these advantages there is the possibility of easily modifying the G-CODE linked to the production of the components of the equipment system, using parametric software, in order to "adapt" them to the geometric and morphological characteristics of different theatres. Using a digital interface, it is therefore possible to create a flexible and adaptable equipment system with the same logic and speed: an integrated, multi-scalar approach (DfMA - Design for Manufacturing and Assembly) that combines Design for Manufacturing (DFM) and Design for Assembly (DFA) methodologies.

The integration between the digital environment and digital production opens up new opportunities also linked to staff training through the use of the digital twin. The training of workers who operate in contexts of high archaeological value requires, in fact, specific staff training in order to reduce the risk of damaging the monument. Added to this advantage is also that of safety in the workplace. By simulating the operations to be carried out in a digital environment, in addition to training the workers, it is possible to preventively evaluate the risks associated with the specificities of the construction site. Based on the experience and data collected, the research proposes to extend the methodology developed to other theaters in eastern Sicily for their sustainable use and valorization, improving their accessibility also for new forms of entertainment.

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Credits

The study is the result of the collaboration between the three authors. In particular, L. Alini wrote the paragraphs 2.1, 4, 4.1, 4.2; R. Valenti wrote paragraphs 1, 2, 3, 3.3; E. Paternò wrote the paragraphs 3.1, 3.2; S. Martinez wrote paragraph 5.

Photographic Credits

Archive *Environmental Design Laboratory* figg. 7, 8

Archive LaRa figg. 1, 2

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