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INTEGRATED 3D SURVEY METHODOLOGIES AND DIGITAL PLATFORMS FOR THE ENHANCEMENT OF ARCHAEOLOGICAL DATA IN THE DIGITAL TRANSITION

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Abstract

This paper examines the current and crucial issue of the digitisation of Cultural heritage as it is applied to the archaeological field. It addresses the difficulties of managing and handling big data from archaeological parks that require software, dedicated systems and specific skills, which often result in the transition to digital being perceived as an end in itself. The research focuses on the case study of the archaeological site of Sepino in Molise (Italy) and proposes a workflow for the realisation and subsequent processing of the 3D survey of archaeological parks, recognising that the survey is the first step towards digitalisation. Secondly, it proposes solutions for the consultation, management and valorisation of the surveyed assets, mainly oriented towards dissemination.

Keywords

Cultural Heritage, Digital Transition, CH Digitalization, Archaeological Heritage, 3D integrated survey, Photogrammetry, Laser scanner, 3D model, Retopology, Physically Based Rendering, Texture maps, Digital platforms, Data management, Archaeological Site of Sepino

Introduction

Digitalization has become an inescapable step in the process of knowing, preserving, and enhancing Cultural Heritage. Indeed, it not only offers new opportunities for the enjoyment of Cultural Heritage subject to deterioration or now lost, but also serves as an investigative tool and aid for specialized studies, knowledge dissemination, and is capable of enriching the range of interpretations on existing heritage with new meanings (Pagliano, 2023). Among the various disciplines that have relied on the benefits of digital, archaeology began to take its first steps in this direction in the last decades of the last century by first experimenting with the resources offered by Geographical Information Systems (GIS) and, subsequently, the additional potential introduced by the third dimension, which has great utility in both technical-scientific and tourist-disclosure contexts (Mastronuzzi, 2020). The creation of 3D models requires a previous process of reverse engineering that, thanks to three-dimensional surveys of the real asset, allows its morphology to be reconstructed in a digital space. This particular scientific-disciplinary sector, over the years, has benefitted from the implementation of new intervention procedures and a profound methodological renewal, facilitated by the rapid development of electronic and information technologies. This has resulted in a significant simplification of the data acquisition phase as well as a refinement in their processing. All this has made it possible to accurately survey even very complex environments in a much shorter time than in the past, achieving a level of detail in documentation largely unattainable with traditional survey techniques (Galera-Rodríguez, 2022). However, this process inevitably clashes with the extent, heterogeneity and complexity inherent in archaeological realities. The sheer data size, the limitations of commonly used technological means, the lack of knowledge and competence by managing institutions and professionals also pose significant constraints on the usability of the produced elaborations, especially in the case of large-scale assets. Thus, the need for a standard that facilitates the transition to digital has arisen. To tackle this problem, the paper presents the work carried out on the Archaeological Site of Sepino in Molise (Italy), This site has been selected by the Italian Ministry of Culture (MiC) as a case study to structure workflows and functional solutions for the digitalisation of archaeological sites throughout the Country, with the hope of contributing to the preservation and enhancement of the Cultural Heritage they contain and the promotion of scientific research in this field.

1.1 Survey methods for the archaeological assets

Archaeology is undoubtedly a varied and complex field of application for surveying. The first aspect to emphasise is that the need to survey artefacts that have already been excavated and whose state of preservation needs to be documented at the time of the survey is compounded by the need to intervene during excavation campaigns as an inherently destructive activity (Carandini, 2000; D'Andrea, 2006). The survey of archaeological assets also often requires a multiscale approach, as it is necessary to move simultaneously from the survey of the site to that of the individual artefact. The concept of multiscalarity is also applied in cases where highly accurate surveys of an object are inserted into a less detailed survey of the context: these are quite different issues that require distinct instruments that, although operating with non-homogeneous accuracies, must somehow interact with each other (Bitelli, 2002). Another aspect is the accuracy required of the survey itself. This may not be very high if the primary objective is the effectiveness of the presentation and visualisation of the object (see use in the field of dissemination); on the other hand, specialist users may require very high precision and resolution.

Finally, in some contexts, metric data must be obtained as quickly as possible in order to limit or minimise disruption to excavation, or if the object is subject to particular environmental constraints (Bitelli, 2002). With these considerations in mind, it is easy to see that in many cases it is necessary to integrate techniques operating at different scales, or products generated using different reference systems, within the same survey. The choice of multiple surveying techniques is not only useful for producing more complete products, but also for verifying and establishing the metric validity of the data obtained. Current geomatics technologies offer opportunities of great interest in terms of both the primary moment of survey and data representation for objects of archaeological interest (Bitelli, 2002; Girelli, 2007, Remondino, 2010).

In general, a first step in surveying is to define reference points or, where these do not exist, a materialised frame network over the area of interest in order to georeference the site. In this sense, GNNS (Global Navigation Satellite System) is certainly the most widely used technology in a large number of experiments, especially in relation to surveying in the archaeological field. The ability of GPS (Global Positioning System) to survey with uniform precision and georeferencing, in a globally defined reference system, is essential for setting up new networks or for integrating existing networks based on different systems or created in different periods (Girelli, 2007).

For example, GPS is often used as the basis for integrating data (mostly open and closed polygons) obtained with traditional topographic surveying instruments such as the total station into a single reference system. The total station is a relatively simple instrument to use, although its productivity is now reduced compared to new technologies, especially in the case of complex surveys. Despite practical problems related to environmental conditions, possible difficulties in setting up points in protected areas and data processing problems, including conversion between different systems, the total station is still used today because of the high accuracy of its measurements, which is far superior to that offered by GPS alone. In addition to the instruments employed in a classical topographic survey, there are also laser scanners (airborne or terrestrial) and photogrammetric (airborne or close-range) surveys, which collectively form the essential basis for a 3D survey. This is because they respectively permit the direct or indirect detection of point clouds in a three-dimensional space (Remondino, 2010). In the past, the most prevalent technique for the survey of cultural heritage was photogrammetry, combined with topographic surveying for the acquisition of control points. The advent of scanning lasers, along with the vast quantity of data that could be collected and the remarkable speed of acquisition enabled by this methodology, initially led to the proposal of a potential substitution between the two techniques. However, the international scientific community has since recognised the integrated use of the two methodologies as the optimal solution for metrically accurate surveys, one that can fully describe an object in terms of its detail. It is obvious that the outcome of the survey must encompass not only the delineation of the object's shape, dimensions, and proportions (which can be accurately determined through laser scanning), but also the identification of its current condition and the extent of its deterioration (Bitelli, 2002). This is crucial for evaluating the most appropriate intervention strategies for preserving the asset. Only photogrammetric surveys can provide the comprehensive data required for this assessment.

In conclusion, the various techniques described are perfectly complementary. While photogrammetry produces a model that is readily interpretable using the acquired colourimetric and material information, laser scanning is able to automatically describe the three-dimensional geometry of an object with high resolution. Finally, integration of data acquired with GPS and total station provides the three-dimensional surveys with georeferencing. However, it is important to note that this approach presents an increasing challenge in terms of data management, particularly in terms of storage space. The amount of raw survey data is not only affected by the introduction of new technologies that allow for the acquisition of an ever-increasing amount of data, but also by the collection of material from multiple instruments. In such circumstances, it is of the utmost importance to ensure that the work is correctly designed a *priori*, in terms of both operational procedures in the field and data storage and subsequent processing (Parrinello & Porcheddu, 2023). Furthermore, as will be demonstrated in the subsequent case study, it is also advisable to adopt calculation techniques and procedures that allow for interoperability between different datasets, in order to fully exploit the benefits of an integrated survey.

1.2 Systems for the use and management of survey products in archaeology

The complexity and articulation of digital surveys in archaeology has, over time, required the use of different systems for the management and utilisation of the products of campaigns which can be in two- or three-dimensional form, and have technical-scientific or dissemination purposes.

Since the 1990s, the acceleration of technological advancement has led to the introduction of a number of new tools, including GISs (Geographical Information System), which have since become a key component of the technical and scientific landscape for the management of 2D information in the archaeological sector (Valenti, 1998, 2000; D'Andrea, 2006). The adoption of GISs has had a significant impact on the methodology employed in research, ensuring the effective implementation of tools and techniques for the documentation and analysis of data (Salzotti, 2012). Based on data extrapolated from the surveys, the utilisation of GIS tools in the context of archaeological sites that are already in light or excavation campaigns that are in progress enables the user to comprehensively encompass the diverse and evolving phases of work by selectively adopting the most pertinent functionalities at designated intervals, contingent upon the specific requirements of the task at hand. Information systems facilitate a range of data management activities, from basic data entry and organization according to thematic categories to more advanced operations such as database query, measurement, processing, and spatial and predictive analysis. The main advantage of GIS platforms over more conventional methods is the assurance of uninterrupted and progressive control over the research process. This eliminates the necessity for a fixed and sequential approach, allowing for a more flexible and continuous updating of the stages of progress, which can be conducted in parallel (Valenti, 1998, 2000; D'Andrea, 2006; Salzotti, 2012). Despite its long-standing adoption, this approach continues to be regarded as a strategic solution, particularly within the technical and scientific domains. This is evidenced by the sustained success of the Pyarchinit plugin for Q-GIS among archaeologists (Mandolesi et al., 2022), as well as the utilisation of georeferenced 2D spatial databases even within the cutting-edge management systems of the Archaeological Park of Paestum and Velia (Zuchtriegel et al., 2022), of the Via Appia one, (Quilici, Roascio, Paolillo, Oliva, Spallino, Picchione, Reginaldi, Rocchetta, Iovine, Brumana, Previtali, Banfi, Roncoroni, Stanga, Attico, Bertola, & Gabriele, 2022) and Archaeological Park of the Colosseum (Della Giovanpaola, 2021; Parco Colosseo, 2023). However, the increasing amount and variety of complex information to handle inevitably reduces the exclusive usability of 2D visualisation. For everything that is inherently three-dimensional, including an archaeological site, representation by means of 3D models helps to improve not only the visualisation or preservation of information but, above all, its definition, simplifying its organisation and integrating the restitution with a cognitive data system. In recent years, research in this field has been developing, focusing on the use of digital 3D models as a 3D database, seen as a vast, ordered cognitive system of spatial information, which can be modified and implemented over time (Valzano, 2020).

For the archaeologist, this represents a great leap forward: the transition from textual databases to visual databases, with hypermedia and multimedia possibilities, makes it possible to have at one's disposal tools capable of bringing together and integrating a large amount of heterogeneous data and making them available in an intuitive as well as logical form, ranging in scale from individual artefact to geographical (Gaiani et al., 2011). In this context, the BIM (Building Information Modeling) philosophy applied to CH, i.e. H-BIM (Heritage Building Information Modeling), has aroused great interest. By enabling the integration of geometric and non-geometric information (including tangible and intangible values) and external documents into a single model, H-BIM can become a container for all data related to the property. In recent years, parks such as the Archaeological Park of the Via Appia (Quilici et al., 2022) and the Archaeological Park of the Colosseum (Della Giovanpaola, 2021; Parco Colosseo, 2023) have initiated collaborative research with the Politecnico di Milano.

This research employs the use of H-BIM to collect, catalogue and manage data on the assets being surveyed. This is achieved through the utilisation of 3D models obtained from the processing of recent survey campaigns. The H-BIM effectiveness in the archaeological heritage sector is still under assessment, as it is complex to find a solution that effectively adapts the standardisation logic imposed by BIM to the heterogeneity of archaeological realities (Capparelli, 2019; Doria & Previato, 2024). Building Information Modeling has been utilized to support post-excavation activities; however, it does not encompass all types of spatial data typically encountered in a standard archaeological investigation (Dell'Unto & Landeschi, 2022). In addition, a more advanced overall usability would be achieved at the price of less autonomous usability by archaeologists.

Wanting, a powerful tool that the digital paradigm offers to integrate the 3D model into its geographical context is the aforementioned GIS in the form of 3DGIS. However, GIS software capable of handling real 3D data are quite uncommon, and experiences in handling archaeological data in this sense are still quite experimental. For instance, ESRI has implemented by the time the performance of its ArcGIS Pro for visualising and manipulating data in a 3D environment, including 2D data, drawings, textual information and images (Dell'Unto & Landeschi, 2022); it anyway requires a high level of customisation before it can be used in the archaeological field and, in its full 3D extension, requires significant licence fees.

A further approach to the problem of computerising models is that offered by game-based visualisation systems (GBVS). Unlike 3DGIS or BIM, these allow a more flexible design of graphical interfaces, providing tailor-made solutions for data interaction and visualisation. Such systems can be used, for instance, to evaluate hypotheses, link and explore large archaeological information archives and analyse relationships between landscape and artefacts (Dell'Unto & Landeschi, 2022). On these systems, however, one can see the complexity in the preservation of the reference system for the geolocalisation of artefacts. In addition to these solutions, there are also attempts at combining different technologies, such as the integration of H-BIM and 3DGIS models, or even H-BIM, 3DGIS and GBVS (Ma, 2021; Dell'Unto & Landeschi, 2022). However, it will take time to fully comprehend the potential of such approaches, particularly within the context of archaeology.

2. *Materials*

This work is part of an ambitious project promoted by the Sepino Archaeological Park (PARS) at the behest of the Ministry of Culture (MiC). Following its designation as a New Autonomous Institute in 2021, the MiC has selected this case study as a means of developing a functional workflow for the digitisation of archaeological parks across the national territory. Aim of this approach is to contribute to the safeguarding and enhancement of the cultural heritage contained within these parks, as well as to the advancement of scientific research in this field.

Accordingly, the project entitled "Forma Saepini - Study and Valorisation of the Sepino Archaeological Park: Integrated Surveys," was initiated with the objective of conducting an organic and integrated survey of the entire surface area of the archaeological park.

Despite the Sepino site having a smaller extension than other Italian sites, this characteristic lends itself well to the required experimentation. This is because it makes it easier to study and structure a scalable and repeatable solution in larger and more articulated contexts. Moreover, the diversity of artefacts, which are unevenly distributed across the park's surface, including monuments, archaeological discoveries, rural structures and infrastructure, allows for the extensibility of the proposed solution to be validated in the context of the diverse range of archaeological realities present in Italy.

Saepinum-Altilia is undoubtedly one of the most scientifically significant archaeological sites in the present-day region of Molise. It is particularly impressive in terms of its visual impact for visitors (Ciliberto, 2015). The settlement occupies an area of approximately 13 hectares in the plain at the foot of the Matese, situated in proximity to the valley of the Tammaro river. It lies along the historic sheep track, the Pescasseroli-Candela route, which has been used for transhumance of flocks from Abruzzo to Apulia since ancient times. The town's prosperity is also due to its geographical position, which was undoubtedly strategic, and which facilitated the early development of the area between the 4th and 2nd centuries BC. The city reached its greatest splendour during the Roman period, the time when its typical road layout was established, comprising a *cardo* and a *decumanus*, the latter coinciding with the *tratturo*. (Cianfarani, 1954, 1958; Matteini Chiari, 1982; Santillo et al., 2022).

In the city, archaeological structures from the Samnite and Roman periods coexist with contemporary rural edifices dating back to the 18th and 19th centuries (Fig. 1). In addition to the city walls, which still stand today and along which the remains of 19 of the 35 original towers are visible, there are numerous other structures of interest, including a theatre, a forum, thermal baths, a *basilica*, a *macellum*, places of worship, and rooms connected to the commercial activities related to transhumance (Matteini Chiari, 1982).

The current appearance of Altilia is the result of the efforts of individuals such as Valerio Cianfarani, the Superintendent Archaeologist of Abruzzo and Molise.

Fig. 1: Aerial view of the Sepino Archaeological Park (retrieved from “FORMA SAEPINI. Studio e valorizzazione del Parco Archeologico di Sepino”)

From 1950 onwards, he has been responsible for the excavation and restoration of several key sites, including the *forum* and basilica, part of the city walls, the theatre, Porta Boiano (one of the four city gates), and numerous buildings on the *decumanus* that were used as private dwellings and shops (*tabernae*)(Cianfarani, 1954, 1958; Matteini Chiari, 1982). Another significant figure in the history of the park is Adriano La Regina, an archaeologist who was instrumental in preserving the rural cottages that emerged on the hemicycle of the middle quarry of the theatre. These structures serve as crucial evidence of the city's historical evolution (Matteini Chiari, 1982). Despite this and taking into account the unorthodox research methods used by Cianfarani during his excavations (Matteini Chiari, 1982), we are still far from being able to reconstruct an organic and detailed picture of the phases of the city's life. In fact, almost none of the buildings that have come to light, whether public or private, have received a complete excavation edition with a reasoned architectural reconstruction and an exhaustive study of the material that may have been found. (Ciliberto, 2015).

3. *Methods*

A first step was taken with the creation of the PARS, which called for the implementation of an integrated survey campaign that, by combining some of the best techniques available today in the field of geomatics with the most advanced methods of 3D metric surveying, would allow a complete study and knowledge of both the built environment and the relative territorial and landscape context of the Sepino Archaeological Park. The results of this initiative will have a positive impact on the institutional activities of the site, making it possible to plan and carry out more efficiently the planned restoration and conservation work, seismic vulnerability studies and excavation campaigns. Finally, it will be possible to activate projects for the use of the site, such as the upgrading of underground utility networks, the maintenance of the road network and green areas, and the removal of architectural barriers. At the end of the work, a local geodetic network will be provided, within which the relevant sub-networks will be defined in order to obtain highly detailed surveys; it is required to provide an analytical picture of the location and consistency of every artefact located in the area and an updated graphic and cartographic view of the Park. Finally, the PARS needs a 3D model of the state of the art, fully navigable, with metric properties, including high-resolution and colour-corrected textures, and optimised for immersive use, to provide a basis for both information and management purposes.

These requirements required a prior study of process optimisation, and therefore the structuring of a workflow that would allow a large quantity of data to be collected in a relatively short time, and then managed, simplified and enjoyed, ensuring very high technical and scientific quality. The responsibility for surveying the park was assigned to ACAS3D Soluzioni Digitali srl, a company established as a spin-off of the University of Pisa. By assembling a team comprising individuals with diverse and complementary professional expertise, the company was able to address the challenges inherent in the three-dimensional survey of a substantial asset in an innovative manner, thereby facilitating its evaluation.

3.1 The survey campaign

In the initial stages of the survey, a topographical network was established using stainless steel benchmarks with an M10 threaded shank, 40 mm in length and marked with the name of the site (Sepino), the acronym of the Ministry of Culture (MiC) and the reference number of each individual cornerstone. The rationale behind their positioning was to guarantee homogeneity in their distribution across the site, with a particular focus on the areas of greatest interest. From July 2023 to January 2024, a topographical survey of the 36 benchmarks was conducted. This was a preliminary operation that was necessary for the georeferencing of the site which the laser scanning and photogrammetric surveys were to rely upon. The purpose of this operation was to anchor future surveys to known control points, thus contributing to the construction of a coherent and homogeneous database. A mixed survey methodology was employed, combining the use of GPS with a dual-frequency differential satellite receiver (GNSS RTK Leica GS18) and an optical-electronic instrument (Leica TCRP 1201+ total station). The use of GNSS permitted the georeferencing of the benchmarks in accordance with the ETRF2000 (2008.0) reference system. Although GPS offers less precision than a total station survey, this approach is useful when there is a need to georeference a park in an absolute cartographic system shared with other cultural assets. In such cases, it is of great interest to scholars to know the orientation of the archaeological evidence with respect to the cardinal points. Furthermore, should the necessity arise to survey an area beyond the boundaries of the park, lacking any suitable benchmark, the use of GPS would allow for the relatively straightforward integration of new data with existing datasets. The laser scanner survey, which began in June 2023 and completed by January 2024, was conducted with the Leica RTC360 3D laser scanner, with a resolution of 3 mm at 10 m.

Ultimately, it was determined that a combination of terrestrial and aerial photogrammetric surveys would be the most effective approach to ensure optimal data control. In the case of terrestrial photogrammetry, it has always been our practice to conduct the work under the most favourable lighting conditions, with a view to reducing the time required for post-production processing of the acquired data. We have sought to utilise natural and homogeneous lighting wherever feasible; in the event that this was not possible, we employed a Godox AR400 flash unit as an additional source of illumination. The survey was conducted by capturing frames in RAW (.NEF) format with a Nikon D850 camera to which supporting D750 and D800 ones were added. An average design GSD had to be chosen from the outset: taking the sensor size of the D850 (36 x 24 mm), the pixel size on the sensor (0.004 mm) and a focal length of 35 mm as a reference, and identifying a shooting distance of approximately 4 m from the subject was identified in order to have a GSD of 0.5 mm. Fixed optics chosen from 35 mm, 50 mm and 60 mm were used, with the exception of particularly narrow areas where the 15-30 mm was required. During the days of the campaign, it was essential to use an X-Rite ColorChecker Passport Photo 2 to optimise the colorimetric calibration in post-production. It was necessary to take photos with the ColorChecker in the scene every 15 minutes at the most, or in any case at every evident change in lighting; in cases of substantial variations in lighting conditions, the session was suspended to avoid excessive problems later on.

The aerial photogrammetric survey was conducted with the aid of a DJI Mavic 2 Pro drone, with the goal of minimising shadows on the ground. The Hasselblad L1D-20c camera, mounted on the device, has a 1-inch, 20-megapixel CMOS sensor. Two distinct flight altitudes had been identified beforehand, each offering a unique advantage in managing the survey at varying levels of detail. The first altitude, set at 40 m from the ground, was designed to provide an expansive overview of the park, while the second, situated at 20 m, was tailored to facilitate detailed surveys of the archaeological evidence.

This approach enabled the acquisition of data pertaining to the roofs of the most recent buildings, as well as insights into the city gates. A total of 36 targets were previously positioned on the surface of the park and surveyed with GPS in order to georeference the model in post-production. In this instance, ColorCheckers were also employed, and their management proved to be more straightforward than in the case of terrestrial photogrammetry, given that flight times were less than 15 minutes. The survey campaign that was conducted resulted in the acquisition of approximately 700,000 frames and 2226 scans, which collectively reached a raw data weight of 30 terabytes.

From this, it is quite obvious that the data resulting from this process is inherently complex. This is due not only to its size, which requires the use of adequate servers or storage to accommodate it, but also because of the way it is processed. This involves the utilisation of sophisticated hardware and software tools. It was precisely because of this complexity that it was essential to identify an appropriate methodology for the management and subsequent utilisation of the data, which were key elements for achieving the objectives of knowledge and the valorisation of the asset.

3.2 The first steps of post-elaboration

The initial stage of the process entailed a preliminary post-processing of the acquired data. The topographic survey enabled the creation of a network of georeferenced benchmark points in a dual system of local and global coordinates, with an accuracy of less than one centimetre. Indeed, the surveyed measurements were subjected to rigorous compensation through least squares coupling with the absolute coordinates of the GPS system, via rigid roto-translation.

In order to prevent deformation during the alignment process, the network was constrained to the coordinates of a single point and a direction, which was defined by a GPS RTK survey. The transverse Mercator projection can be applied to derive UTM-ETRF2000 map plane coordinates (east, north, elevation) from a set of geographical coordinates. These coordinates exhibit a distinctive property, namely a minor linear deformation even at the local scale. This phenomenon can potentially give rise to discrepancies between GPS and total station measurements at large spatial scales.

To address this issue, it was determined that a locally adapted Eulerian coordinate system would be the most suitable solution. The laser scans were aligned with one another, and the resulting point clouds were roto-translated rigidly with respect to the SR of the topographic survey, yielding an average subcentimetric alignment error. In order to facilitate this process, laser targets were strategically positioned during the survey phase. These were subsequently collimated with a total station, by establishing a station on the previously surveyed benchmarks, and scanned with laser scanners.

This approach expedited the processing time, as the Register 360 program was employed to structure the fundamental laser project, and more expedient software, such as Scene and JRC, was utilized to align the remaining scans at a later stage using the cloud-to-cloud technique.

Upon completion of the processing, the recorded scans were exported in e.57 format, which is compatible with the 3D model management software. The frames were then homogenised on Adobe Lightroom by adjusting the image parameters and correcting the colourimetric values using the ColorChecker.

Lightroom is the optimal software for these steps because, unlike Adobe Photoshop, it allows modifications to be made to multiple frames simultaneously, ensuring greater processing speed of the datasets, which is especially crucial when handling a substantial amount of information, as in this case. Despite the attention devoted to the variation of illumination during the survey phase, it was necessary to ensure that the frames relating to the same environment were as uniform as possible. This was achieved through the editing of the associated adjustments. It is crucial to underscore that all the aforementioned "colour correction" processes necessitated a preliminary and meticulous "colour management," which entailed the calibration of the monitors on which the images were displayed, to ensure the standardisation of the colour display profiles of the media being worked on. Subsequently, the images were exported in uncompressed .jpg format, which was deemed the optimal choice for the clients' purposes. This format limits the data's heaviness, facilitates consultation, and reduces the cost of the storage memory needed to contain it. The sRGB colour space was selected due to its compatibility with the majority of screens on the market, despite the chromatic limitations that penalise the range of blues and greens. Subsequently, the frames captured by the drone were processed in Lightroom and imported into Metashape for the generation of the point cloud. Following the acquisition of the textured mesh, an overall orthophoto of the site was created, which will subsequently serve as a cartographic base. Additionally, the DSM (Digital Surface Model) was extracted.

3.3 The second steps of post-elaboration: the choice of Reality Capture

As previously stated, the integration of data obtained through disparate survey methodologies has become a crucial aspect of research due to its undeniable efficacy. Accordingly, the PARS expressly called for the creation of an integrated survey instrument that would employ laser scanning in conjunction with specialized equipment for topographic and photogrammetric surveying. In order to adopt this methodology, the most common approach is to engage in manual dialogue between the data extrapolated from laser scanning processing software and those obtained from photogrammetry programs. Furthermore, the positioning of a substantial number of targets on the property under study must be planned and implemented in advance. These targets must then be surveyed with all the instruments typically used in rural settings. This allows the coordinates of each target displayed in the frames to be assigned using dedicated software, with the coordinates obtained from the laser scans serving as the reference point. It is evident that such an approach limits the effective management of the survey, both during the on-site data collection phase and in the subsequent post-processing phase. Firstly, it is crucial to recognise that the application of targets to protected assets is not always feasible, given that these assets are susceptible to rapid deterioration. Secondly, the integration of missing data from areas covered by the targets represents a significant challenge, particularly when the survey area extends to 13 hectares. In light of the excessive expense of the aforementioned approach, it was resolved to pursue an alternative methodology that would integrate laser and photogrammetric surveying within a unified software platform. The software selected for this purpose is Reality Capture (RC)[1], a programme designed to accelerate the post-processing phase of data, facilitating the creation of digital models and thereby increasing productivity while simultaneously reducing labour costs. In order to fulfil the requirements of the PARS programme as effectively as possible, namely to create models of the entire archaeological park that can be easily managed with the available computer tools, and to limit the time required for processing the raw data, it was decided to work by subdividing the project into partial three-dimensional models and to accompany this approach with the use of LoDs (Level of Detail). The most practical solution entailed the creation of three-dimensional models of the individual structure, with the most suitable LoD selected according to their extent. Additionally, models of the individual elements that make up the structures were created, should these be of particular value. In the latter case, it was decided that a LoD higher than that chosen for the entire structure should be applied, given that the surface to be treated was smaller. The project

[1] The software, released by the Slovak company Capturing Reality in 2013 and purchased by Epic Games in March 2021, is a useful tool for the creation of three-dimensional models obtained from LiDAR or photogrammetric surveying, or from the integration of the two through the use of the SFM algorithm.

was structured so to allowe the partial models to be combined to create an overall model of the entire park. The processing of individual portions of the property and subsequent integration was a viable option because all the elements had been georeferenced in advance relative to the same reference system. This enabled the extent of the area to be calibrated from time to time according to the computing power of the available computers. In order to test the methodology, which was subsequently to be extended to the entire park, the basilica and the *macellum* were selected as the pilot structures (Fig. 2).

Fig. 2: The illustration presents a top view of the forensic area and the basilica at the cardo and decumanus junction (https://www.ilgiornaledellarte.com/Articolo/sepino-paesaggio-armonico-ancora-incontaminato/)

The basilica, situated within the forensic area at the intersection of the cardo and decumanus, served as a multifunctional space where commercial transactions and judicial proceedings occurred. Additionally, it served as a venue for social interaction and respite (Fig. 3).

Fig. 3: View of the basilica (https://www.vacanzeinmolise.it/visitare-gli-scavi-archeologici-di-sepino/)

The *macellum*, situated along the *decumanus* in close proximity to the basilica, served as the market, a commercial establishment where foodstuffs and everyday items were sold (Fig. 4).

Fig. 4: The *macellum* (Soprintendenza Archeologica del Molise)

3.4 The third steps of post-elaboration: the integration between the different output of survey campaign

In order for the laser and photogrammetric data to be integrated, RC converts each spherical scan into a cube, comprising six faces, called quadrics, which represent its in-plane development. The six quadrics, although analogous to photographic images, retain the geometric properties of the scans (scale and reference system), thus obviating the necessity for the markers typically required to georeference and scale photogrammetric data (Fig. 5).

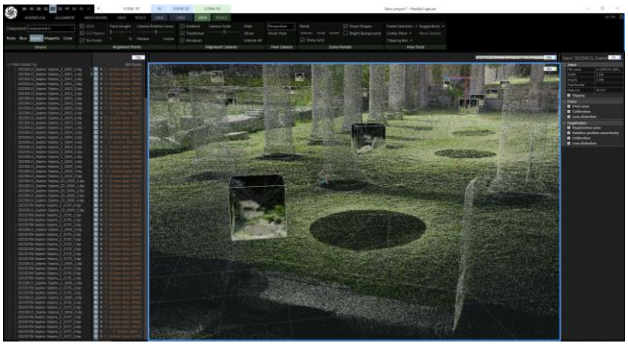

Fig. 5: Tie points and quadric cloud visualisation

This approach enables the production of metrically accurate and visually appealing results with a single tool. It is crucial to highlight that the search for homologous points between quadrics and frames necessitated the multiplication of the typical station points for a laser survey. This is because the optimal results are achieved when the surveyed points are also framed as perpendicularly as possible to the instrument. To illustrate, if a single scan is insufficient to fully describe an element, such as a 30-metre wall, six scans are required for the case study (Fig. 6).

Fig. 6: Locating station points with the laser scanner in the survey phase by visualising quadrics in Reality Capture.

This requirement may appear somewhat time-consuming, but due to the technical characteristics of the current equipment and the subsequent acceleration of the integration processes for the survey, it was considered to be the optimal choice, particularly in view of the size of the entire park.

The output of this processing step is a photogrammetric survey scaled and georeferenced in the laser scanning reference system (Fig. 7).

Fig. 7: Mode of displaying the alignment of frames to quadrics.

Subsequently, the high-poly HP meshes (with a maximum number of polygons) were created, which were handled by Reality Capture through the utilisation of depth maps.

Then the texturisation process of the model was undertaken in two phases: the unwrapping phase and the subsequent application of the texture. In particular, the process of unwrapping involves the transposition of a three-dimensional mesh into two-dimensional information through the use of cuts, thereby facilitating the optimal application of a two-dimensional texture to the model. This is a crucial stage, particularly when the morphology of the objects is complex, as the visual quality of the model is contingent upon its precision. For this reason, depending on the objective, this phase is managed manually by experienced operators. In this specific case, however, given the objective of the research, it was considered too time-consuming to foresee, and thus we opted for the semi-automatic tool 'Unwrap' offered by RC. This tool allows the user to manage the number of textures to be generated and their maximum resolution.

The initial processing stages yielded the HP models of the basilica and *macellum*, which exhibited a high degree of metric and visual quality but required a considerable amount of storage space (Fig. 8).

Fig. 8: Textured models of the basilica and macellum.

3.5 Retopology and PBR

The initial findings of this elaboration confirm the extent to which contemporary surveying technologies guarantee an excellent correlation between the physical asset and its digital representation. This is a crucial objective in the domain of CH, although it does necessitate a significant investment of resources in terms of memory, connectivity and processing. It is therefore essential to determine the optimal quality to reserve for the various disciplines and fields of application and to identify the most effective solutions for its management. Although high-quality models were essential for obtaining technical-scientific products such as the commonly used orthophotos, an alternative approach was sought that would be more suited to the specific context. In order to facilitate the consultation and management of the surveyed data by PARS, retopology and PBR (Physically Based Rendering) techniques were employed, through which an attempt was made to identify an optimal balance between geometric fidelity, visual quality, and heavy processing output. Retopology represents a comprehensive approach to mesh optimisation, with the primary aim of reducing the polycount (number of polygons). It is regarded as one of the most challenging tasks in three-dimensional modelling, necessitating considerable expertise and dedication from the modeller. However, over the past few years, several alternatives have been developed that can reduce production times by automating, partially or entirely, the repetitive actions required by manual methods (Garone, 2017). In light of the above, the research project evaluated the semi-automatic functions of Reality Capture. While this approach does not allow for complete control over the topological properties of the mesh, it does facilitate the standardisation of the chosen workflow across diverse environments and elements within the park (Fig. 9).

To address the inevitable loss of detail that is inherent to the retopology process, a solution has been implemented that enables the replacement of the model with one that is lighter but comparable in appearance to the original: PBR techniques. This is a three-dimensional rendering technology that applies the principles of physics to model the interaction between light and matter. It interprets the colours and textures of materials applied to the scene as they would appear in reality.

Although a physics-based approach may appear to be the most logical method for creating a photorealistic representation, it is a technique that has only been widely adopted in the last ten years or so, mainly for offline rendering of films and interactive rendering in gaming (Pharr et al., 2023).

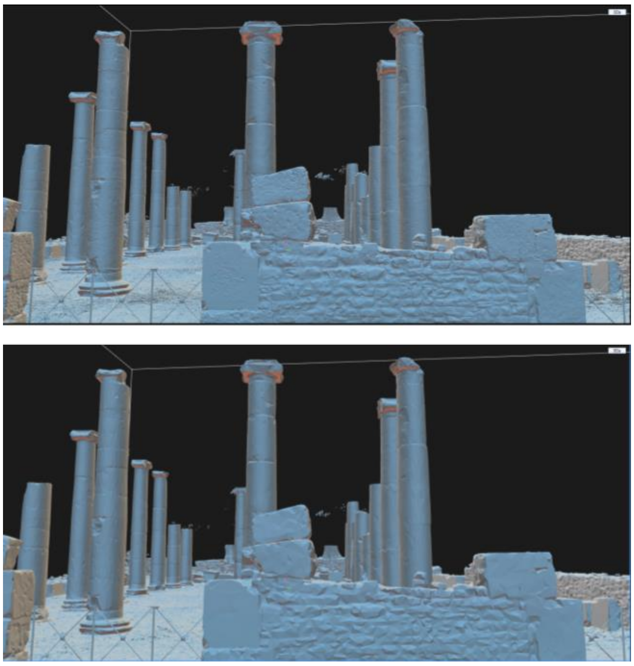

Fig. 9: Basilica model before and after retopology.

In addition to the development of algorithms to simulate the effects of light on materials, PBR is based on the storage of information about the details of objects in particular 2D maps or textures. These can be overlaid and combined in order to simulate the surface morphology of objects. The generation of textures is achieved through an operation known as baking.

This involves the saving of the characteristics of a high poly (HP) model in maps, which are then applied to a low poly (LP) model in order to simulate specific effects. Once the textures have been obtained, they are reworked on the surface of the model by means of a shader, which is a program that determines the external appearance of the object, taking into account both the light conditions and the information provided by the textures (Garone, 2017).

In the specific case of the project, it was decided to use only the albedo map[2] and the normal map[3] among the many existing ones, in order to standardise a fast process that could be replicated for all the park's environments and to

[2] The albedo map defines the colour of an object at each point, without the influence of shadows or reflections.

[3] The normal map stores the orientation of the mesh polygons in three-dimensional space, thereby ensuring that they reflect light in a realistic manner when exposed to light sources.

obtain products that were streamlined in terms of byte weight (Fig. 10).

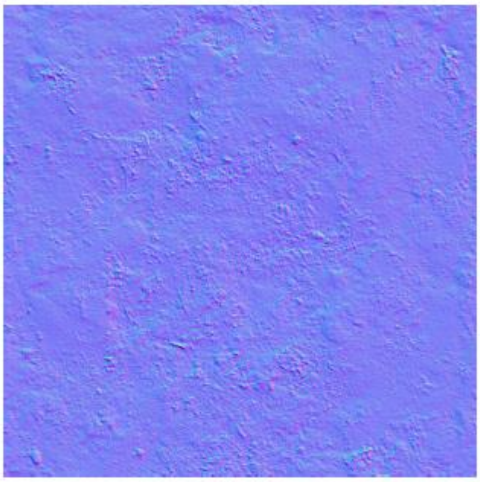

Fig. 10: Normal map examples (Garone, 2017)

Following the simplification of the model, the UV mapping calculated on the high-poly mesh is no longer suitable for the low-poly mesh. This is due to the decimation of triangles, which prevents many texels from finding a polygon to match. As a result, considerable distortion occurs when reapplying the texture to the decimated model.

A new UV mapping is therefore necessary in order to prepare the maps of the HP model for projection onto the LP model. The subsequent stage is the reprojection of the texture on the low-poly mesh, which allows for the simulation of details that are no longer represented at the polygon level. This approach offers the significant benefit of enabling the management of individual effects through exclusive 2D work, as it is no longer the model that interacts with the light, but the maps themselves. While the albedo map is essential for accurately representing the original in digital form, it is the application of the normal map that provides the most insight into the capabilities of PBR logic.

Ultimately, the model exhibited errors due to the erroneous positioning of normals on select polygonal faces. It was postulated that this issue may have originated from an excessively restrictive decision during the decimation phase or from the inherent limitations of RC's internal unwrap tool. To assess with certainty the source of the problem, it was resolved to test the *Smart UV Project* tool offered by Blender, which gave excellent results and solved the problem.

The methodology used gave excellent results:

- LP models, characterised by poor material realism, reproduced the original model more faithfully after applying the normal map. In particular, the realistic rendering compared to the HP model can be better appreciated by testing how the simplified models react dynamically to changes in the lighting sources.
- By exporting the meshes with attached textures in .obj format, the weight of the models was reduced by about 250 times compared to the originals, while maintaining more than adequate geometric quality.

It is therefore believed that the workflow identified can be a valid compromise for the graphic restoration of the 24 terabytes of models covering all the environments of the Archaeological Park, and a suitable delivery product for the dissemination purposes in which PARS is interested.

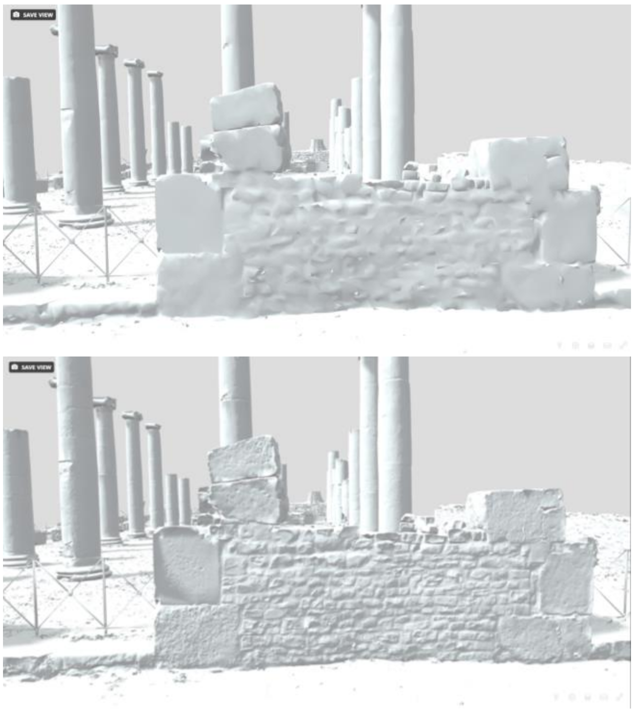

Fig. 11: Simplified Basilica model before and after normal map reprojection.

3.6 User platforms for simplified three-dimensional models

As previously stated, the PARS is allocating its resources to promote the enhancement of the Sepino Archaeological Park. While the development of a platform aimed at the scientific understanding of the property is a strategic objective, the Park Authority is pursuing a synergistic approach with a tourism-oriented project that will reveal the beauty of this relatively unknown place to the general public, stimulate interest and encourage investment. In response to this need, two alternative solutions were put forth, which can be adapted in accordance with the developments of the current project.

The initial proposal is the straightforward publication of models on Sketchfab, which permits the importation of .obj models accompanied by up to three 8k textures. As the second one, a prototype dissemination platform was developed using the Unreal Engine.

The user interface (UI) of the system was developed for use on computers or touchscreen devices within the museum area of the park. However, to ensure comprehensive accessibility, it would be sensible to create a version optimised for use on smartphones. The layout of the entire project was designed in accordance with the rebranding of the site, which occurred subsequent to its designation as an Archaeological Park.

The selection of content and navigation mode was delineated with the intent of offering the end user an intuitive, engaging interface with the possibility of varying levels of in-depth analysis according to their interest. The platform is structured into four thematic macro-areas, each associated with a quadrant in the park's logo. Interacting with the coloured areas leads to the exploration of a specific field of investigation.

Fig. 12: Platform's start page.

The first area focuses on the promotion of the exhibitions and museums within the park. In particular, the Museum of the City and Territory of Sepino, the exhibition entitled "Fascinosa Sepino: Two Centuries of Travel, Discoveries and Excavations in Altilia" and the lapidarium must be mentioned. The second quadrant has been designed to facilitate access to the 'Augmented Reality' function, which can be activated by visitors during their physical tour of the park. This will be achieved through the GPS system of their mobile device, which will track their position at all times. This will enable them to access audiovisual content that will appear directly on their screen by framing the various environments and assets in the city with their smartphone. This will accompany their visit.

The third and fourth quadrants are developed around the navigation of an interactive three-dimensional map that can also be experienced in a first-person perspective. By accessing the 'Virtual Tour' area, the screen presents the simplified 3D model of the park, which is freely navigable by the user. Accompanying this is a narrator's voice that provides the user with a description of the park and its features, as well as a narrative of the history of Saepinum. It is possible to alter the lighting of the model, regulate the transparency of the surveyed trees and display the various construction phases of the city. In the bottom right-hand corner, a 2D map is always displayed, indicating the user's actual position in relation to the 3D model. The platform is structured in multiscale mode, thereby facilitating access to increasingly detailed information.

The primary visualisation is that of an overall 3D model of the park, which has been suitably retopologised and does not incorporate the albedo map, thus limiting the heaviness of the data. By hovering the cursor over the symbols in the vicinity of the various structures, the name of the specific building can be displayed, allowing access to the corresponding higher-resolution, textured model. Even in this further interface, navigation is unrestricted, and historical information or further insights and media can be accessed by clicking the display. When deemed necessary, some specific environments allow for a further level of detail, such as one of the basilica's walls which features an inscription on its surface.

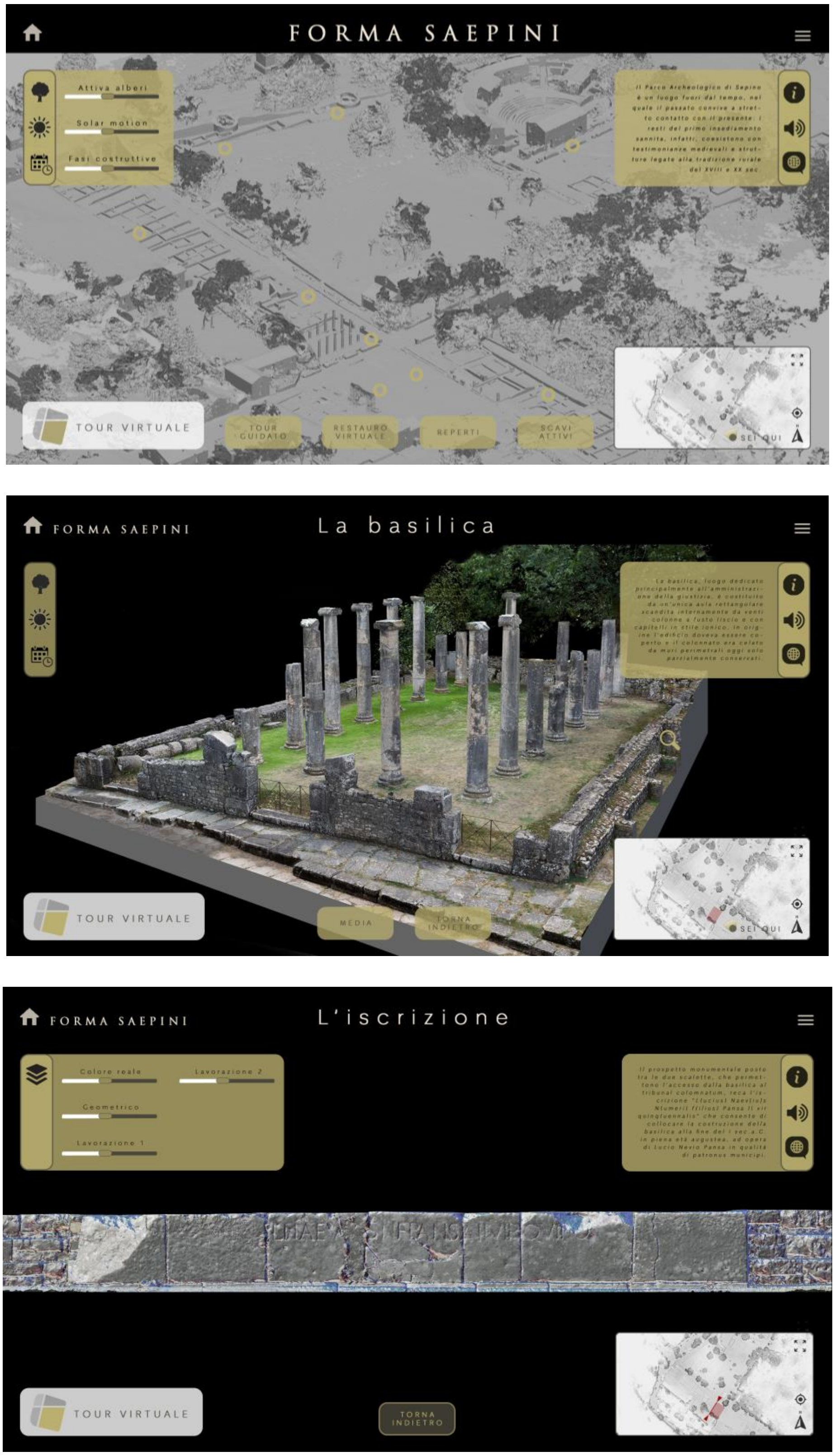

Fig. 13: The three levels of depth available on the platform.

A specific tool was designed to initialise an automatic tour of the model, and a 3D reconstructive hypothesis of the Roman-age city in comparison with the current version was included; a concise overview of Sepino's most notable discoveries at the site of their excavation is available for consultation and insights into ongoing or recently concluded archaeological investigations facilitates a deeper comprehension of their significance and contributes to the site's ever-increasing knowledge base.

4. Conclusions

In recent years, there has been a notable acceleration and expansion of the digitisation process, which has now become a pervasive phenomenon across all domains of Cultural Heritage, including archaeology. Some of Italy's most significant archaeological parks are pioneering the integration of emerging technologies into existing management and interpretation methodologies, with the objective of enhancing the protected heritage through digital means. Nevertheless, this is a complex and multifaceted undertaking that necessitates comprehensive research and analysis to identify the most appropriate criteria for integrating the traditional and the new knowledge models.

In this context, the article put forward a functional workflow for the digitisation of the pilot case study of the Sepino Archaeological Park, defining a workflow for the realisation and processing of the 3D survey, which could be applied to other archaeological sites in Italy.

It was thus necessary, in the first instance, to identify the most suitable approach to address this challenge. The integration of different surveying techniques proved to be a fundamental choice in order to obtain a qualitatively relevant result and to optimise the use of available resources, both in the data acquisition phase and in view of its post-production.

Specifically, a topographical support network was created through the joint use of GNSS and a total station. A 3D survey was then conducted using laser scanners and terrestrial and aerial photogrammetry, with particular attention paid to the metric and formal quality of the data, as well as the speed of execution. Given the considerable volume of data acquired, the Reality Capture software was selected for post-processing due to its ability to facilitate the alignment of data from the georeferenced laser survey with that from the photogrammetric survey. This decision necessitated the design of in-situ campaigns to ensure their implementation. The need to multiply the number of laser scans in comparison to the number typically required did not result in an actual extension of time. This was made possible by two factors: firstly, the new laser scanners have the capacity to deliver high-quality performance in a very short time; secondly, the additional time taken was compensated for by the speed at which the surveys were unified. Although the user interface is not intuitively designed, RC proved to be a valid support in the processing of the data, guaranteeing excellent results comparable to those of more widely used software, such as Metashape, but with much shorter timescales.

The initial phase of post-production yielded the textured meshes of the basilica and the *macellum*, the selected environments for experimentation. These meshes exhibited a high degree of quality but also a considerable volume of data, which proved incompatible with subsequent use. It was of fundamental importance for the purpose of the project to identify an effective solution for the management of three-dimensional models of the entire park area, which would combine high quality with a limited occupation of storage space. Specifically, technologies were employed that entailed the geometric simplification of the models through retopology techniques and the application of 2D maps to simulate the geometric and material detail in a manner that retained a high degree of realism. This solution enabled the generation of highly streamlined models of the basilica and the *macellum*, while maintaining a high level of fidelity to the originals. Without this approach, it would not have been possible to use the models in applications intended for professionals working on the archeological asset and the wide audience, let alone the model of the entire park.

It is of the utmost importance to consider this aspect, as it is not uncommon for clients of projects to receive products of the highest quality, yet find them unusable due to the excessive data volume, limited technological capabilities, and lack of expertise in data access tools. The digitisation process is an end in itself in the absence of solutions that enable the valorisation of the acquired data. With this in mind, the second phase of the work involved the design of a functional platform for the dissemination of knowledge about the archaeological site. This was done in order to meet the PARS's need for a tool that would increase the attractiveness of the site using innovative visualisation methods. Specifically, the Unreal Engine platform allows users to freely navigate through the different environments that make up the park at the desired level of detail. The current design allows for the potential implementation of interfaces that are compatible with the platform and suitable for utilisation by the scientific community. It would be beneficial to assess the effectiveness of a multi-user approach that can address the needs of two distinct audiences, with a particular focus on the challenge of maintaining the geo-referencing of the model, which is crucial for technical and scientific studies.

In conclusion, it is hypothesised that, given the current technologies and the requirements expressed by PARS, the proposed solutions could be valid solutions both for the initial phase of 3D survey and data processing, as well as subsequent phases of consultation, management and valorisation through digital platforms aimed at the general public. Furthermore, the advanced solutions are designed to be replicable at other archaeological sites, thereby providing valuable support to managing bodies and public administrations in addressing the challenges associated with the digitisation of heritage.

Data Availability Statement

The research results presented are the outcomes of a M.Sc. thesis by the author S.B. discussed at the University of Pisa in 2024 and conducted under the supervision of A.P., M.G.B., F.C. and G.C. The master thesis is available on request from the author.

Conflicts of Interest

The authors declare no conflict of interest.

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