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Review

Digital Tools for Data Acquisition and Heritage Management in Archaeology and Their Impact on Archaeological Practices

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Abstract: The significance of data acquisition in archaeological practice has consistently held great importance. Over the past few decades, the growing prevalence of digitization in acquiring data has significantly transformed the landscape of archaeological fieldwork, influencing both methodology and interpretation. The integration of digital photogrammetry and laser scanning technologies in archaeology has transformed data acquisition, enabling efficient and precise documentation. However, this digital shift raises concerns about information overload, the potential loss of on-site insights, and the need for suitable data management methods. Over the past 15 years, digital tools like photogrammetry, laser scanning, and unmanned aerial vehicles have advanced cultural heritage documentation. These methods offer detailed 3D models of archaeological sites, artifacts, and monuments, with evolving accessibility and user friendliness. This paper delves into methods for documenting cultural heritage, examining the implications of various approaches on the archaeologist's workflow and on the field as a whole.

Keywords: archaeology; digital technology; data acquisition; cultural heritage; photogrammetry; laser scanning; data management; archaeological inquiry; information systems

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Citation: Moullou, D.; Vital, R.; Sylaiou, S.; Ragia, L. Digital Tools for Data Acquisition and Heritage Management in Archaeology and Their Impact on Archaeological Practices. *Heritage* **2024**, *7*, 107–121. https://doi.org/10.3390/heritage7010005

Academic Editor: Marco Gaiani

Received: 17 November 2023
Revised: 20 December 2023
Accepted: 22 December 2023
Published: 26 December 2023

1. Introduction

The advent of digital photogrammetry and laser technologies has markedly transformed the approach to data acquisition at archaeological sites. While archaeology, as an inherently destructive science, encourages the collection of extensive data, the influx of copious information presents the challenge of potentially concealing critical insights under the weight of irrelevant details. Additionally, the substantial reduction in on-site data acquisition time, and the transition of data management from the field to the office due to digitalization, introduces concerns regarding the loss of valuable archaeological information derived from direct on-site observations.

This concern is heightened by the challenges of revisiting stratigraphic data and the inherent uncertainties associated with the archaeological excavation process and initial stages of interpretation. As the time spent on site for data acquisition is significantly reduced and the information is stored digitally, a substantial portion of field documentation has shifted from the field to the office.

Despite the apparent benefits in terms of cost, time, and data acquisition efficiency, there is a notable risk of overlooking crucial archaeological insights derived from on-site observations. Furthermore, the inability to double-check stratigraphic data and the uncertainties inherent in archaeological excavation and initial interpretation stages pose ongoing challenges. Complications may also arise when excavation drawings and 3D models of monuments are created by individuals who were not present during excavations or lack the necessary training to understand and interpret monuments or excavations [1].

With the emergence and adoption of new technologies in archaeology, there is a surge in data, yet the corresponding procedures and methods for effective management are lacking. The initial challenge stems from the segregation of data into isolated silos, impeding the establishment of connections between different data types. The second issue lies in the sheer volume of data, presenting a formidable obstacle to systematic organization and analysis.

To prepare for future technologies, we require new procedures and methods that facilitate the handling of unforeseen data that these innovations will bring. Additionally, we draw inspiration from other scientific fields that employ information systems to transform vast datasets into meaningful information. This approach enables us to effectively utilize the data we are currently collecting.

Nonetheless, a crucial question emerges: Is it viable to treat archaeology as an information system workflow, irrespective of whether activities take place on or off site, or should the processes of documentation and interpretation "return" to the archaeological site, irrespective of the technology employed for data acquisition?

2. Documentation of Cultural Heritage Sites and Artefacts. Development of Digital Tools over the Past 15 Years

Cultural heritage faces ongoing peril from natural hazards, climate change, and human-made disasters. Safeguarding this heritage is crucial for its societal role in preserving artifacts, values, and, in certain instances, entire cultures for future generations. This preservation facilitates interpretation and, notably, fosters the growth of cultural tourism. Specifically, the destructive nature of archaeological excavation demands prompt and precise recording at each stage [2]. Cultural heritage documentation involves the safeguarding and monitoring of both tangible and intangible heritage, focusing on the capture and generation of data and information. Its significance is underscored by international entities like ICOMOS, which prioritize best practices, guidelines, and standards. The ongoing evolution of technology aligns with the continual enhancement in digital documentation processes for cultural heritage. The European Union places a premium on the digitization of cultural heritage, emphasizing its pivotal role in the European Agenda for Culture (2007/C 287/01), while also intertwining it with sustainability (2014/C 183/08).

Digital tools have infiltrated the field of archaeology since the early 1950s [3]. The early use of digital tools in archaeology concerned text-based analysis, searching, and archiving. The field that started developing was "humanities computing", which started the shift within archaeology for knowledge and expertise that were not traditionally involved in the discipline. Today, digital tools have brought on profound changes in the way archaeological knowledge is produced. The field of archaeology, like many fields in the humanities, requires interdisciplinarity with new expertise invading the field like computer sciences, software engineering, software technicians, photographers, drone operators, 3D modelers, and others [4].

These methods and techniques significantly expedited the archaeological team's work on site. Depending on the site's size, this approach enabled the team to produce highly accurate documentation of the existing conditions within several hours or days.

2.1. Digital Photogrammetry and Laser Scanning

Laser scanning methods and digital photogrammetry techniques have been employed for metric data acquisition in cultural heritage documentation since the 1990s [5]. Both aerial photogrammetry and close-range or terrestrial photogrammetry have been widely used. The 3D scanning technique offers a fast and methodical way of obtaining geometric data of cultural heritage [6]. Today, documentation of cultural heritage sites and artifacts can be broadly categorized into three methods: image-based, non-image-based, and combinative techniques [7].

Image-based methods, which include photogrammetry, can be categorized into three types: panoramic, close-range, and UAV-based. The evolution of technology and the accessibility of affordable, powerful digital photographic equipment have brought about a revolution in this field. Photogrammetry techniques developed over the past two decades enable comprehensive documentation, resulting in three-dimensional models with high-quality and realistic textures. Structure from Motion (SfM) has been heavily used in the last few years and has undoubtedly fundamentally changed the way cultural heritage is modeled. It is a technique that combines photogrammetry and computer vision, and is particularly widespread due to its easy use and low economic cost [8,9]. The appearance of unmanned aerial vehicles has radically changed the way archaeological sites and excavations are documented because these provide a fast and economical way of surveying them by capturing high-spatial-resolution data [10]. However, challenges such as the requirement for pre-planning and expertise in data processing add complexity to this process. Each of these three photogrammetry methods presents its own set of obstacles. Panoramic photogrammetry is constrained by angles, close-range encounters challenges related to camera resolution and processing issues, and UAV-based methods are susceptible to weather conditions, wind, weight capacity limitations, and stability issues.

Additionally, infrared (IR) photographic documentation offers advantages but has its limitations [11,12]. Retrospective photogrammetry refers to the use of historical photographs or images to extract 3D geometric and geospatial information about objects, landscapes, or structures from the past. This technique involves analyzing old photographs and using them to recreate the three-dimensional geometry of the depicted scene or object [13]. Typically, it involves identifying reference points or features in old photographs, and then using software and mathematical algorithms to reconstruct the spatial information. It is often used in historic preservation, archaeology, and urban planning to understand changes over time and to create accurate 3D models or maps of historical sites or structures [14,15]. This can be a valuable tool for documenting and preserving cultural heritage or understanding the evolution of landscapes and structures over time, provided that suitable photographs exist in an archive [13].

Total stations, as non-image-based documentation tools, have been employed in topographical surveys for several decades. They can document a restricted number of points on a site and provide precise geo-referenced locations for these points. Historically, archaeologists utilized these points to scale and position their drawings and measurements of the site, obtained through more traditional methods like tape measures and sketching. Over the last two decades, architectural laser scanners have emerged, capable of capturing millions of points from the surroundings and generating a point cloud for highly accurate documentation of the site. This is a computer-controlled method that may integrate GNSS and unmanned aerial vehicle (UAV) photogrammetry, and produces 3D models [16]. Their use for cultural heritage documentation has been immensely increased [17]. The simultaneous use of cameras and scanners, often known as structured-light techniques, has become increasingly prominent. It involves using cameras and scanners together to capture and process data about objects or scenes. The integration of these data-gathering devices with corresponding modeling, data-processing, and implementation solutions is crucial for making this method effective.

Laser scanning finds applications in various cultural heritage projects. The Global Survey has emphasized the significant role of laser scanning in heritage conservation, citing projects such as the Notre-Dame Cathedral in Paris, the Opera House Theater in Rhode Island, the Royal Palace in Madrid, and the Statue of Liberty in New York City [18]. It also enables the digital reconstruction of sculptures, architectural pieces, and artworks. The production of molds and duplicates for outdoor CH artifacts facing preservation constraints is another valuable application. Laser additive technology is an efficient method for making replicas [19]. Laser scanners measure distances from non-contact objects, making them suitable for monuments as they have no negative impact on the original structure [20,21].

Terrestrial laser scanning, categorized as a non-image-based documentation method, proves to be time efficient, capable of capturing hundreds of points per second, and effective in acquiring precise data. The primary challenge lies in processing large volumes of data comprehensively and in an automated manner, from initial data collection to the generation of the final product [22]. Terrestrial Laser Scanner, being a robotic method, is well suited for documenting surfaces and objects in confined spaces.

However, as a non-image-based method, laser scanning has limitations in rendering detailed edges, colors, and minor surface features such as cracks. While LIDAR excels in area scanning, it still encounters challenges in visually representing target surfaces. One significant drawback is its inability to measure surfaces outside the scanner's line of sight. This results in holes and issues in the point cloud data, impacting the realism of 3D models [23,24]. Various approaches have been proposed to address these issues [25–27], although 3D model generation from laser scanner data remains a time-consuming process, requiring several days to clean point cloud data. A summary of problems with laser scanning can be found in [28–30].

The type of material of the object to be scanned significantly affects the quality of laser data. Opaque and diffusely reflective surfaces create challenges, and post-processing is needed to fill holes [31]. Different approaches, such as positive definite Radial Basis Functions (RBF) and volumetric diffusion, have been proposed for hole filling [32,33]. The importance of cleaning the point cloud is emphasized in [34].

The third category of cultural heritage documentation, which integrates laser scanning and image-capturing technologies, brings the advantages of swift and precise point plotting along with realistic rendering of textures and imagery. Hybrid methods, such as mobile mapping, are increasingly employed, utilizing photogrammetry, INS/GNSS, and laser scanning. These approaches, however, necessitate the synchronization, overlaying, and integration of data, posing a challenge that is being addressed through the development appropriate software and methods. Photogrammetry can furnish a substantial amount of accurate 3D georeferenced data with texture, but it requires traditional field survey measurements to establish a reference frame [35].

All the aforementioned methods provide accurate and detailed recording, 3D photorealistic visualization, and documentation of data applicable to various contexts, including urban areas [36], archaeological sites and monuments [37,38], as well as artworks [39]. Furthermore, these methods not only save time and resources but also facilitate the recording of monuments that would have been otherwise inaccessible. This was notably exemplified by the case of the Athenian Acropolis Circuit wall and the underlying rock, where the monument's size and the physical challenges associated with its examination precluded the use of traditional methods [40]. Consequently, the assessment of its condition and subsequent restoration efforts commenced only after the completion of documentation using photogrammetric and laser scanning techniques [41].

Although digital documentation technologies offer immense assistance, several significant barriers impeded their widespread adoption. These barriers included the necessity for specialized and expensive equipment, a reliance on highly trained scientists for operation, and a lack of user friendliness. Moreover, whether used in combination or individually, these methods proved to be suitable only for specific cases, requiring specialists to carefully select the most appropriate approach for their tasks. This underscores the crucial role of the human factor in tool selection and emphasizes the necessity for a variety of digital-technology-based methods to meet the diverse needs of cultural heritage documentation.

The development of streamlined software–hardware solutions is crucial to facilitate data gathering, processing, and model rendering. Achieving this requires creative and hybrid approaches that can adapt to the intricate nature of cultural sites and artifacts. Cultural heritage cases vary in size, shape, texture, and other factors, leading to a need for diverse digital-technology-based methods to address a wide range of tasks [35,42].

These methods, however, have undergone continuous development in software, hardware, and procedures. In the past decade, significant efforts have been made to streamline procedures and reduce the required time. This has resulted in the emergence of low-cost equipment and simplified processes. Presently, a wide range of documentation solutions is available, encompassing sophisticated systems as well as user-friendly options such as smartphones and tablets. With the assistance of photogrammetric software, even non-professional users can generate high-quality three-dimensional models. Consequently, there is an urgent need to explore techniques capable of handling multiscale, multitype, and temporal data.

2.2. Machine Learning and Artificial Intelligence

The last three decades have seen extensive utilization of machine learning (ML) algorithms across various applications, including industry, engineering, finance, and medicine. The fundamental concept revolves around "learning from experience", making it a subfield of computer science and artificial intelligence (AI) that focuses on using data and algorithms to simulate human learning processes. Machine learning empowers computers to learn from data, identify patterns and relationships, and subsequently make predictions based on those data. In recent years, machine learning has found applications in archaeological data. Archaeological data are categorized into the following types: (a) numerical and/or categorical data, (b) textual data, (c) images, and (d) spatial data [43].

For textual data, different approaches employ machine learning techniques. One example is the creation of a training dataset for Dutch Named Entity Recognition (NER) in archaeology [44]. This dataset supports semantic search in archaeology, aiding archaeologists in locating structured information within the vast Dutch excavation reports. A cloud-based tool was developed for processing textual archaeological records, capable of browsing large online knowledge resources, learning on demand, and generating semantic metadata. These metadata can be combined with data from various areas to create machine learning scenarios [45]. Machine learning techniques have also been applied to automatically annotate tangible and intangible heritage, as well as modern theories and methods of archaeological thought [46].

Machine learning has been predominantly applied to images in archaeology, particularly for object recognition. Various approaches exist, such as the extraction of structural elements of buildings using deep neural network architectures [47]. The detection of ancient rock carvings using a deep-learning-based approach has also been described [48]. Another approach extracts monument architecture and important features of monuments from images using Neural Network [49]. Other studies present the application of machine learning for pottery sherd detection from drone-acquired imagery [50,51], automatic detection of shipwrecks over a large geographic area [52], and the segmentation of petroglyphs from 3D digitized rock surfaces using a Random Forest algorithm [53].

The field of archaeology has globally transformed, particularly in mapping and searching for archaeological sites, owing to the increased availability of large-scale LIDAR, satellite, and aerial images on local, regional, and national scales. Machine learning techniques offer a viable solution for site searches in different locations [54–57].

In geochemistry, the study of the chemical composition of the earth and its rocks and minerals, machine learning is also applied. One research study combines various data sources, trains learning models to classify background and archaeological soils, and assesses the model predictions against established models and current archaeological interpretation [58]. Another study applies machine learning techniques to enhance classification methods for geological flint samples from Wales and England [59].

2.3. GIS

The Geographic Information System (GIS) is designed to capture, analyze, manage, store, and present spatial or geographical data. GIS allows for the creation of detailed maps and the analysis of various data types within a geographic context. GIS plays a crucial role in archaeology by enabling researchers to effectively manage, analyze, and visualize spatial data related to past human activities and landscapes. Archaeologists use GIS to map excavation sites, record artifact distributions, and analyze the topography of ancient settlements. By integrating various data sources such as satellite imagery, historical maps, and field surveys, GIS helps archaeologists uncover patterns, identify potential excavation locations, and understand the context in which historical events occurred [60–62]. For a critical perspective on GIS, mapping and spatial thinking in archaeology, see [63,64].

2.4. Data Storage

With the development of technology and applications in archaeology, today, we face a new set of challenges created by the large and complex volumes of archaeological data. We are now discussing Big Data for archaeology, which is a result of the enormous size and complexity of the data we use and produce. Given that some of them are georeferenced, we delve into the realm of Geospatial Big Data (GBD) for archaeology. Geospatial Big Data are broadly defined as datasets with locational information that exceed the capacity of widely available hardware, software, and/or human resources [65].

Archaeological data are inherently complex due to its volume, diverse data sources, and the dynamic nature of its changes. Understanding and utilizing these data are facilitated by the incorporation of metadata, providing additional contextual information such as the date of collection, methodologies employed, and specific conditions or limitations associated with the data. Furthermore, the inclusion of paradata becomes imperative, offering insights into the process of data creation, decision making during research, and details about workflow, data collection techniques, and any modifications applied during the research process [66,67].

Historical data, influenced by individual interpretation, are collected by people and are subject to the time and place of acquisition. Importantly, much of these data exist in non-digital forms and may never be digitized, adding complexity to the storage challenge. In the comprehensive analysis carried out by Child and Terry in 2022 [68], the storage of archaeological data is discussed as a significant challenge for scientists, historians, and archaeologists. Perspectives suggest that workflows in archaeology and heritage management are increasingly digital, emphasizing the importance of storing and preserving data [69,70]. Organizations extensively use databases to collect, store, and reuse data [71–73]. Despite the availability of cloud platforms today, offering tools for data storage and management, the storage of archaeological data remains complex due to multiple data formats, sources, and a lack of clear understanding of how to interpret and use historical material. Integrating robust metadata and paradata practices becomes crucial for addressing these challenges and ensuring the transparency, reproducibility, and integrity of archaeological research.

2.5. GPR

Geophysical prospection has become an invaluable tool for archaeologists exploring ancient sites without excavation [74]. This non-invasive method employs a range of techniques, such as Ground Penetrating Radar (GPR), gradiometry, and electrical resistivity (ERT), to uncover buried structures, artifacts, and even entire landscapes. These methods offer several advantages, including minimal disruption to archaeological sites and cost efficiency.

Ground Penetrating Radar (GPR) is a particularly useful tool in this regard. It utilizes radar pulses to create subsurface images, helping archaeologists identify hidden features without disturbing the soil [75]. Magnetic Gradiometry (MG) is also widely employed in documenting archaeological sites that are preserved underground. MG, with its sensitivity to variations in the magnetic field, can discern the presence of buried structures and artifacts without causing any harm to the archaeological treasures hidden beneath [76]. Conversely, ERT involves measuring the electrical resistivity of subsurface materials by injecting electrical currents into the ground and recording potential differences. ERT, as it has a large detection depth, provides invaluable insights into the distribution of geological formations, groundwater, buried objects, and archaeological features [77,78].

2.6. VR/AR Technologies

Virtual Reality (VR) is a technology that immerses users in a computer-generated, three-dimensional environment, simulating a realistic and interactive experience. Users typically wear a VR headset that tracks their head movements, providing the sensation of being present in a virtual world. This technology often incorporates audio, haptic feedback, and hand controllers to enhance the immersive experience, making it suitable for various applications, including gaming, education, training, and simulations. Augmented Reality (AR) is a technology that blends digital information and virtual elements with the real world. AR typically involves the use of a device, such as a smartphone or smart glasses, to overlay computer-generated graphics, text, or audio onto the user's view of the physical environment. This enhances the user's perception of reality by providing additional context, information, or interactivity.

Both technologies have made significant contributions to archaeology, transforming how researchers study and present archaeological sites and artifacts. Numerous VR/AR applications in archaeology strive to improve and augment visitors' experiences during museum exhibitions or on-site excursions [79]. This technology can be utilized, for instance, to establish virtual platforms for analyzing distant archaeological sites [80] or for conducting time-based studies of intricate underwater archaeological excavations [81].

2.7. HBIM

Historic Building Information Modeling (HBIM) technology has been in use for several years, primarily as a means of managing historical buildings. This methodology involves gathering terrestrial laser data and integrating these with digital images. Subsequently, using specialized software, the point cloud is aligned with the digital image to generate 3D models of the historical structures [82]. The challenges that require further investigation include the initial enhancement in the model's geometry to ensure that the point cloud ultimately yields precise engineering drawings. The virtual reconstruction process of cultural heritage is complex, given the intricacy, diversity, and irregularity of historical objects. Some characteristics and morphologies are not adequately represented in BIM software libraries. To model the various virtual parametric components, it is crucial to integrate the point clouds with historical and technical approaches [83–85].

3. Utilizing Digitally Derived Documentation Data to Address Archaeological Inquiries

Technology has long played a crucial role in archaeology, particularly with the use of instruments like active sensors and image-based 3D reconstruction techniques. However, it is only in recent years that these data have been consistently used to support investigations within archaeological sites [86–91]. Alongside this, there has been a growing demand for a deeper understanding of how archaeology is practiced in the modern digital age and how digital technologies and methods are influencing and reshaping the field. This includes the actual fieldwork and practices employed by archaeologists, the tools and equipment (apparatuses) they utilize, as well as the intellectual and knowledge-related aspects of their work [92–95].

Three-dimensional models resulting from 3D field acquisition campaigns have proven to be a valuable tool for several purposes [92]: (a) creating highly precise sections, two-dimensional maps and three-dimensional models of the archaeological site [90,96,97]; (b) monitoring the activities carried out by archaeologists on site [98]; (c) examining the spatial relationships between various materials unearthed at the site [97,99]; and (d) enabling specialists to conduct more precise analyses of the materials excavated during the archaeological dig [100].

Indeed, the data generated from the precise 3D models have been proved highly effective in addressing archaeological and historical questions. A noteworthy instance involves the interpretation of a substantial structural failure identified in a section of the North Fortification Wall of the Athenian Acropolis. In accordance with historical and archaeological evidence, this failure occurred sometime after the middle of the 18th century until the early 19th century, encompassing several characteristics:

(a) The collapse of the upper part of the wall, constructed from architectural elements of the entablature of the Old Temple of Athena;
(b) A notable outward lean (7 cm) of the remaining lower section (beneath the collapsed crown);
(c) An approximate one-degree rotation;
(d) Systematic cracking of the wall's outward face.

Employing a back-analysis utilizing the precise model derived from laser scanning data, it was possible to ascertain that the cause of the failure was an earthquake with specific characteristics. By examining the historical seismicity of the region, the timeframe of the 1805 earthquake was established [101].

Today, we have access to abundant data on archaeological sites. The current challenge lies in effectively managing and organizing these data while maintaining up-to-date and easily accessible databases [95]. This challenge has led to the demand for new specialists in archaeology, including experts in data management, technicians proficient in operating equipment, 3D modelers capable of working with photogrammetry models and 3D point clouds, and personnel providing IT infrastructure support.

As digital tools and other disciplines increasingly integrate into the field of archaeology, new challenges emerge.

New Fields Developing within Archaeology. Excavation Recording Systems

Archaeological research relies on excavation as a fundamental process to access and interpret archaeological material, which serves as a rich source of information about past events and societies. Excavation is essentially a scientific procedure conducted to retrieve and observe material remains associated with past human activities. It is a process that involves not only data collection but also the creation of a detailed record, transforming the excavation site into a valuable information archive. Despite the destruction of the physical artifacts during excavation, the documentation and systematic recording of findings are considered essential as the excavation is viewed as an "unrepeatable experiment" [63].

The excavation record serves as the primary medium for subsequent archaeological interpretation. It allows for continuous interaction with the archaeological site's historical information and plays a crucial role in the development of interpretations at various scales. The importance of the excavation record extends beyond the fieldwork phase. It facilitates the successive transformation of the excavation archive, enabling researchers to revisit and verify interpretations by tracing the interpretative steps from the excavation event to publication [95]. This chain of references enhances the credibility of archaeological research.

Approaching archaeological research through the lens of an information system, encompassing the entire process from fieldwork to the publication stage, offers the opportunity to develop bespoke software solutions tailored to the specific demands of archaeology. In order to facilitate the excavation recording process, as well as the subsequent analysis interpretation and publication processes, digital excavation recording systems for the documentation, analysis, and publication of archaeological data are created. This approach offers the advantage of consolidating all information into a single, cross-referenced repository. Such software, for example, iDig—Recording Archaeology [102,103] and Inari AIS [104], extends beyond mere data storage and presentation. For an overview of relative software, see [105,106], with bibliography. For an excavation recording system that involves the creation and utilization of 3D models by archaeologists while they are in the field, see [92].

This consolidation paves the way for the creation of tools designed to democratize advanced statistical analysis, thereby widening accessibility to a broader spectrum of researchers and stakeholders. The significance of this approach lies in its capacity to streamline the archaeologist's workload, optimizing efficiency and resource allocation. In that way, the archaeologist's workload is theoretically reduced instead of being increased, and the archaeologist can focus on the archaeological questions that need to be answered. However, it is crucial to acknowledge the technological dependencies involved in using these tools. The successful implementation of such tools relies on robust infrastructure, including reliable access to electricity and specialized expertise. In regions with limited resources, where archaeological endeavors often take place, these dependencies pose significant challenges. The absence of reliable power sources and a shortage of experts proficient in utilizing advanced technologies may hinder the effective adoption of these tools. In such cases, we often see the use of remote sensing [107]. Addressing these challenges is essential to ensure that the democratization of such digital tools is not only conceptual but also practical, allowing archaeological research to flourish in diverse geographic and resource-constrained settings.

In adopting an information system perspective toward archaeological excavation, the process of field documentation can be deconstructed into discrete components for meticulous examination. This multifaceted process encompasses documentation, the archaeologists themselves, the software employed, and the hardware technologies utilized in data acquisition. The execution of the excavation is guided by theoretical constructs and models, which, in turn, shape the methods and implementations applied, thereby influencing both data collection and the overarching workflow. The raw data are acquired through various hardware instruments, including laser scanners, total stations, and cameras, in conjunction with manually entered data, subject to interpretation by the overseeing archaeologist.

The integration of an information system facilitates the systematic documentation of these data, orchestrating the data's progression through layers of specialized software before ultimately being stored within a centralized database. These information systems also empower users to access the data, apply filters, and transform the data into meaningful, contextually relevant information. This paradigm allows archaeologists to interact with the software, fine-tuning parameters and refining their understanding of the diverse facets of excavation data.

The practice of data transformation and integration, as demonstrated in this context, mirrors well-established conventions in other domains handling extensive datasets, notably in the financial sector. For archaeology, this signifies a progressive avenue toward achieving a more comprehensive understanding of archaeological sites. It furnishes researchers with advanced tools for more streamlined investigations that span multiple excavation sites and geographic regions. It is important to emphasize, however, that while such software solutions do not supplant the intrinsic insights derived from on-site observations, they provide archaeologists with the means to document a greater extent of the site and utilize the amassed data more effectively in their research endeavors.

Modern information systems, such as the ones mentioned above, come equipped with customizable features, allowing for the adaptation of documentation procedures to suit the unique requirements of individual excavations. These systems also provide essential search and analysis capabilities, enabling tasks such as the classification of pottery shards based on specific criteria. Furthermore, they support more complex analytical processes and facilitate data export to standard file formats for use in a wide range of software applications. Additionally, these systems are designed to integrate selected data with external systems through industry-standard protocols. A crucial aspect of information systems in this context is their ability to address the increasing documentation requirements set forth by relevant authorities, streamlining the process and expediting compliance.

Harnessing the advantages of information systems to manage the substantial volume of data generated by emerging technologies equips archaeologists with the ability to conduct comprehensive data analysis, even years after the completion of an excavation, while minimizing the loss of critical information. These innovations assist in addressing the backlog of archaeological data and hold the potential to unveil novel insights, thereby allowing archaeologists to concentrate on their core competencies: critical thinking, exploration, and interpretation.

The advantages of efficiently using archaeological information systems are numerous and the integration of digital workflows has become so fundamental to the research process that it influences the way knowledge is created [108,109]. In addition, using digital documentation for a cultural heritage site opens avenues for the creation of applications such as augmented reality in archaeological parks, virtual platforms enabling online visits to reconstructed archaeological sites, and VR portals offering immersive experiences in historical settings, allowing users to explore architecture, literature, and politics of the past. Once a site is digitized into a three-dimensional database, it becomes a versatile resource for constructing realistic models of its existing condition and exploring various reconstruction theories. Augmented reality on tablets and smartphones facilitates dynamic, on-location views of diverse reconstructions for the general audience. Interactive interfaces on smart devices provide additional access to information, including architectural drawings, archival images, removed artifacts, and expert notes. Consequently, the digitization of a site positively impacts its representation in preservation processes, whether physical or virtual reconstruction [110].

However, a notable critique arises from their use [111]. In addition to potential compatibility issues and challenges in long-term data preservation [95], challenges emerge within the archaeological community. Archaeologists needing more technological proficiency may encounter difficulties in employing these systems and effectively documenting their findings, potentially leading them to delegate the task to more technologically adept archaeologists or even colleagues from other disciplines. This technological proficiency gap could result in a hierarchical division of labor, where those proficient in technology handle the data management and system operation. In contrast, others may feel increasingly distanced from the recording and interpretative processes. Additionally, this may lead archaeologists to reduce their physical interaction with archaeological remains during the recording process, as some may postpone primary recording until they are back in the laboratory [111]. This shift could minimize the hands-on engagement with archaeological remains during the fieldwork phase, potentially causing oversights in subtle contextual details crucial for a comprehensive understanding of the site.

4. Conclusions

In summary, the practical application of techniques such as photogrammetry, lasers, UAVs, and IT tools has proven exceptionally valuable for archaeologists and cultural heritage specialists in documenting and preserving cultural heritage. These methods yield reliable and high-spatial-resolution results, making archaeological findings and excavations known. Inaccessible or geographically challenging areas have been successfully captured through the application of these techniques. The primary goal of cultural heritage is to inspire people to explore and understand their history over time. The new recording and visualization methods for cultural heritage locations and events significantly contribute to a better understanding of past events.

However, the highly complex archaeological environment and the vast amount of data pose a challenge in our era of Big Data. Cultural heritage involves heterogeneous data, encompassing texts, historical documents, images, and newly acquired data. In the context of cultural heritage, time and space are intricately linked. Advanced processing and analysis techniques for diverse data types are necessary to capture the complexity of the archaeological context. Achieving knowledge related to cultural heritage requires interdisciplinary collaboration between archaeologists and IT professionals, along with a mutual understanding of the unique concerns of the archaeological scientific field from both perspectives.

The increasingly prevalent approach to archaeology as an information system workflow, whether on or off the excavation site, raises intriguing questions about the evolving nature of archaeological research and data management. Embracing archaeology as an information system workflow implies a comprehensive digital integration of data acquisition, storage, and analysis. This approach is facilitated by contemporary technologies such as laser scanning, photogrammetry, and advanced data management systems. The advantages of this digital workflow are noteworthy, including the ability to efficiently collect vast amounts of data, conduct remote analysis, and facilitate interdisciplinary collaboration. However, this approach poses challenges for the long-term presentation of data, and it may present problems for non-technologically efficient archaeologists who struggle with the integration of digital workflows. Additionally, it may risk detaching archaeologists from the recording process or from direct physical interaction with the site during the recording process, potentially limiting the nuanced insights gained from on-site observations.

For now, the ideal approach lies in a balanced integration of both perspectives. Harnessing digital technologies for data acquisition, management, and initial analysis can significantly enhance the efficiency of archaeological research. However, a complete shift to a 'full digital workflow' may pose challenges. Ultimately, the degree of technological integration in an archaeological project should be context specific, and dependent on research objectives, available resources, personnel, and the nature of the archaeological site in question.

Author Contributions: Conceptualization, D.M., R.V., S.S. and L.R.; methodology, D.M., R.V., S.S. and L.R.; investigation, D.M., R.V., S.S. and L.R.; writing—original draft preparation, D.M., R.V., S.S. and L.R.; writing—review and editing, D.M., R.V., S.S. and L.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data sharing not applicable.

Acknowledgments: Parts of this work were prepared during the COST Action ARKWORK (CA 15201).

Conflicts of Interest: The authors declare no conflict of interest.

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