1 Introduction

1.1 Introduction to the Volume

European archaeology in the 21st century is a digital discipline. It has been argued that 'we are all digital archaeologists' (Morgan and Eve 2012, 523). Isto Huvila has even gone so far as to suggest that 'there is no digital archaeology and no digital society. There is merely archaeology and society, and the digital is a facet of a particular set of technologies and a cultural phenomenon that permeates contemporary existence both when it is present and when it is absent' (2018, 1).

Information collected from fieldwork is either collected digitally or immediately converted from analogue to digital form. Visual archaeological data are all collected digitally, from digital photographs to laser scans. The ways data are managed, curated, and disseminated are essentially all conducted through a digital interface. These digital platforms have changed the way archaeologists consider their obligations to preserve and increase the availability of cultural heritage, and have provided new avenues for archaeology to continue to be a more ethically minded and publicly oriented discipline. However, with all of these changes, the impact that the rapid development of digital technologies has had on European archaeology is difficult to assess because it is so pervasive.

New digital techniques for recording and visualising data retain the underlying principles of archaeology; excavations are conducted in much the same way as they have been over the last half century, spatial data are recorded and collected as they have been, and artefacts are still visually represented. The major changes over the last decade or so have been the platforms, methods, and tools used to record and collect these data. What has also changed is the way archaeologists think about archaeological data and how archaeology is practiced in the 21st century, a century largely defined by digital technology.

This Element will trace these advances and applications in digital technology in European archaeology and how they have transformed the way archaeology is practiced. Various techniques and applications will be viewed through the lens of broad disciplinary change, as archaeologists have moved through stages of initial experimentation to critical assessment of the disciplinary impact that digital tools have on the field of archaeology in Europe. Some of the most recent, innovative uses of these techniques by European archaeologists in different stages of archaeological work, the challenges to the discipline for self-reflexive use of these tools, and their open use in cultural heritage preservation and public engagement will all be discussed.

Obviously when writing about a theme as exceptionally broad as the use of digital technologies in archaeology, no single aspect can be explored completely nor can all aspects be covered. This Element provides a critical review of how some of the most recent digital innovations in archaeological practice are impacting European archaeology today. As such, individual case studies and projects will be highlighted that emphasise certain important characteristics of this 'digital revolution'. There is, of course, no way to properly acknowledge all the work conducted throughout the continent, but this Element will act as a starting point for those less familiar with these techniques, while providing a critical look at the impact of digital technology on archaeology.

1.2 Mainframes and Databanks

Although recent digital innovations have altered archaeological practice in the past two decades, threads of these digital approaches have been present since the 1960s; the 'digital revolution' is now fully matured. Archaeological computing can be traced back half a century to the first use of computers in the 1960s and 1970s (Richards and Ryan 1985). Prior to the widespread use of computer-based applications on archaeological data, following World War II to the mid-1960s, archaeology was a fast-emerging field of quantitative science, developing statistical and graphical approaches that have become the foundation of the modern processing of archaeological data (Djindjian 2009). After some analyses were conducted by using machine-sorted punch cards, pioneering archaeologist Jean-Claude Gardin, with Peter Ihm, were the first to use electronic processing for an archaeological application in 1958 or 1959 (Cowgill 1967; Dallas 2016). At that point computer mainframes were limited to well-funded institutions that could support the air-conditioned, purpose-built facilities necessary to maintain the computers (Lock 2003, 9). The initial foci were information retrieval, statistical computing, data processing, and modelling (Richards and Ryan 1985, 3). Unsurprisingly, the early developments in computing in archaeology were established alongside changes in theoretical approaches in the discipline, such as processual thinking, quantification, neo-evolutionary schema, and scientific approaches (Chenhall 1968; Lock 2003, 8). Gardin's influence on the development of archaeological computing has been unfortunately downplayed (Dallas 2016), but his foundational thinking on archaeological classification and description structured much of the early work in archaeological computing and even permeates some of the most recent developments (Gardin 1971; 1980). Following the work of Gardin and others, the first major advancements in computing in the discipline came in the form of computer-based statistics, specifically multi-variate statistics that drew on a strong European tradition of culture history.[1] Possibly the most illustrative of this early quantitative focus on computer applications in archaeology is Doran and Hodson's 1975 *Mathematics and Computers in Archaeology*.

In the late 1960s and early 1970s Robert Chenhall was an early proponent of utilising the storage capacity of computers to aid in archaeological research. As he noted, 'the computer seems to offer the most logical extension of human mental facilities yet devised, if it can be utilised effectively' (1971, 159). Even in this early period researchers recognised the benefits that computers could provide, supplementing the knowledge capacity of written documents and reports. Unfortunately, the early attempts at creating widespread archaeological databanks did not live up to expectations due to the limits of hardware and storage, lack of institutional support, and the absence of standardisation in what types of archaeological data should be stored (Chenhall 1971; Scholtz and Chenhall 1976).

It was this push towards the use of archaeological databanks that led to the first Archaeological Data Bank Conference in 1971 at the University of Arkansas Museum, US (Watrall 2016). The concept behind this conference, organising archaeologists to discuss the use of computers in research as it related to storing and preserving data, was also foundational for the beginning of the Computer Applications and Quantitative Methods in Archaeology (CAA)[2] conference in 1973, organised in Birmingham, UK.[3] The CAAs have continued to this day with an ever-growing membership.

The early visions for large-scale archaeological computing have begun to be realised. Statistical computing and computational modelling remain important aspects of archaeological research in Europe and computers have provided necessary avenues for the storage, curation, and preservation of digital archaeological data. The push for standardised databanks in the late 1960s and 1970s is finally coming to fruition. Data archiving services such as the Archaeology Data Service (ADS) or the Digital Archaeological Record (tDAR), or country-specific archives such as the Data Archiving and Data Service (DANS) in the Netherlands or the digital services of the German Archaeological Institute (iDAI), are the descendants of databanks proposed in these early years of archaeological computing.[4] Furthermore, larger international digital infrastructures such as ARIADNE and Europeana are connecting data across platforms

[1] Although not all uses of statistical methods in archaeology were appropriate or well done (Thomas 1978).

[2] https://caa-international.org/about/history

[3] See this video on some of the history of the CAA from participants. https://www.sms.cam.ac.uk/media/1357554

[4] See Section 3 for detailed descriptions of these archives.

and repositories, using standardised schema such as CIDOC CRM to address the weakness that Chenhall lamented in the 1970s. As data storage and archiving become a larger focus in Europe, archaeologists are also working to avoid another digital dark age, when data was lost due to corrupted CDs, unreadable file types, changing software, or obsolete hardware (see Jeffrey 2012). Projects such as the COST ACTION 'Saving European Archaeology from the Digital Dark Age' (SEADDA) aim to avoid a further loss of data by developing a series of best practices for the preservation, dissemination, and reuse of archaeological data in Europe.

Although recent digital innovations have altered archaeological practice in the past two decades, the seeds of these digital approaches were planted in the 1960s; the 'revolution' is far from its early stages. In fact, Gary Lock has suggested that the 'digital revolution' actually began just after these early appearances of archaeological computing, with the widespread arrival of the microprocessor in the late 1970s (2003, 10). The shrinking of processors in the early 1970s allowed a move from large mainframe computers and eventually provided the foundation for desktop computing; by the late 1970s microcomputers had become a very real part of archaeological research. The shift in hardware also accompanied a disciplinary shift away from the 'quantitative revolution in archaeology', as Djindjian (2009) terms it, of the mid-1960s to the mid-1970s, to applications for wider use by archaeologists. Computer accessibility continued to increase over the next four decades, leading to the current digital landscape. In this sense archaeology is not at the beginning stages of a disciplinary revolution but well into it (see the historiographic discussions in Djindjian 2009; 2019 and Moscati 2019). This is precisely why in the editorial for the Digital Archaeology special issue of *Frontiers in Digital Humanities* Andre Costopoulos takes the firm stance that archaeology has been digital for forty years (2016). The role of computers in archaeology is not a recent revolution but one that has been steadily developing for decades. At the same time the most recent techniques being adopted by archaeologists, many of which have only become possible due to the exponential growth in computing power, are greatly impacting archaeology in this century.

1.3 Rethinking Archaeology

The growth of these technologies is evident, but what underlies the adoption of these tools is a discipline-wide re-evaluation of the way archaeology is practiced. As Jeremy Huggett suggests in his blog, 'Digital Archaeology should be a means of rethinking archaeology, rather than simply a series of methodologies and techniques' (2016). The challenges that 21st century archaeologists face have not arisen with the adoption of digital tools but have been here the whole time. The transition to these tools has only highlighted, and in some cases exacerbated, these disciplinary dilemmas. This Element will address how different types of digital tools are allowing us to re-think some of these challenges.

Section 2 presents how the role of digital data collection in fieldwork has facilitated significant methodological shifts in the way excavations and surveys are conducted. From mobile digital recording devices to laser scanning to computational photogrammetry, digital tools have been adopted at a rapid pace over the last decade. However, accompanying these adoptions are critiques about the change in excavation methodologies, including the potential for these digital tools to 'de-skill' archaeologists (Caraher 2013; 2016), or the worry that our growing reliance on digital techniques exacerbates a technological fetishism that seems to persist in the discipline.

Section 3 outlines how recent techniques to visualise cultural heritage have been quickly adopted for archaeological research. Digital 3D artefacts, Reflectance Transformation Imaging (RTI), and virtual reconstructions of sites and buildings have all expanded the way archaeologists and non-professionals experience the archaeological record. Their expanding use has also brought to the fore questions of authenticity and authority, questions that in the past were mainly applicable to physical casts, replicas, and illustrated reconstructions.

Echoing larger trends in the sciences and humanities, archaeology has expanded its goals regarding open and accessible data. Section 4 describes how this move attempts to address long-held challenges in archaeological research: how to preserve and curate data for the long term, how to make data useful with other regionally distinct datasets, and how to make these data available to researchers and other stakeholders. Wide-reaching international projects, some funded by the European Union (EU) Commission, have worked to standardise many aspects of archaeological preservation by establishing interconnected digital infrastructures to communicate between datasets using shared ontologies.[5] Additionally, ambitious archiving schema aim to provide access to digital archaeological data for decades to come.

Section 5 outlines some of the outcomes of the widespread use of digital platforms for archaeological research that provide opportunities to include various stakeholders in the archaeological endeavour. Although archaeology has long attempted to be a public discipline, 'digital archaeology of the 21st

[5] In information science, ontologies refer to the structure, formal naming of categories and concepts, and representation of a unified domain of data.

century is necessarily a public archaeology' (Graham et al. 2019). Social media platforms increase not only the reach of archaeological research, but they also create opportunities for interactions between non-archaeologists and archaeologists. In addition, digital tools allow more significant input from those outside traditional disciplinary bounds to shape archaeological research and the ways it impacts communities.

The Element ends by exploring how newly emerging digital approaches may shape European archaeology in the future. The ever-expanding fields of 'Big Data' analysis and machine learning may have drastic implications for the practice of archaeology, moving archaeology further into a data-driven paradigm shift. The accelerated move towards a fully digital discipline also reminds us that we are participating in a larger, digital world, and as a result contribute to global issues of sustainability. Future directions in European archaeology cannot be isolated from international socio-politics but are situated firmly within it.

2 Digital Data Collection in the Field

In a discipline that is prone to conservatism in its methods, the move away from analogue data collection has certainly seemed rapid. But although the transition to primary data collection in digital formats may appear to have happened overnight in archaeology, in truth this process has been accelerating over the last two decades. We are seeing a significant shift to born-digital data collection in European archaeology. The 'born digital' concept is ubiquitous in archaeological discourse at the moment. In the recent volume *Mobilizing the Past for a Digital Future: The Potential of Digital Archaeology* (Averett et al. 2016), a publication focused on new digital collection methods in the field, the term appears forty-three times.[6] The term refers to data that are collected in digital form, never being recorded with a pen and paper but only existing in a digital space. This contrasts with information that was originally collected in analogue form and was then transferred to a digital medium (i.e., digitisation). The term likely has its origin in the mid-to-late 1990s in library contexts, due in part to the digitisation of printed text (versus computer-generated text that could be digitally archived directly). This concept gained a foothold in archaeological research in the early 2000s (e.g., Hopkinson and Winters 2003), due to an increased reliance on digital photography and digital databases for immediate data collection.

The increased use of the term suggests a wider trend in the discipline for transferring documentation of landscapes, sites, and excavation practices directly into a computational environment. The pace of straight-to-digital

[6] This includes a few uses of 'digitally born'.

recording practices has only intensified in the past decade, when mobile tablets, drones, and 3D data-capturing technologies have become less expensive and more user-friendly. At the moment many excavation projects in Europe are generating most of their data with digital techniques. It is safe to assume all projects are using digital cameras to capture visual data, but a growing number use some or all of the following practices to gather data without putting pen to paper.

2.1 Mobile Recording in the Field

Archaeological field collection methods vary widely throughout the world. Mary Leighton's (2015) important comparison of practices in archaeological fieldwork highlighted the lack of standardisation in data collection methods, as well as the practices employed by different archaeological projects. For this reason, it is difficult to generalise about recording practices throughout Europe, in private versus academic contexts, or through the myriad archaeological contexts (single-context versus stratigraphic excavations). However, it appears clear that in the last decade the use of mobile devices for field recording has expanded significantly. In many cases digital devices equipped with proprietary or bespoke software act as the main source of data documentation (see Averett et al. 2016 for numerous examples). A few benefits are clear: by removing the process of analogue recording and subsequent transcription in a digital format, one opportunity for error to creep in is also removed; discrete datasets such as past excavation data, images, maps, and artefact data can all be accessible at once in the field to aid in archaeological choices; one can make use of the different features of the devices such as built-in photography or GPS for enhanced documentation.

The types of software used for digital recording also vary considerably. Although some projects rely on proprietary database systems like FileMaker, others utilise the growing number of generalised open-source platforms for mobile recording (Dufton 2016; Sobotkova et al. 2016). ARK (The Archaeological Recording Kit)[7] developed by LP Archaeology, for example, is a web-based framework for data collection, storage, and visualisation which can be customised for different projects. Another, ArcheoPackPro!, developed within the CONPRA(Contributing the Preventive Archaeology)[8] project, communicates with otherwise independent modular systems to exchange different types of data (Tasić 2017a). Web applications such as ARK and PKapp (Fee 2013) do not require Internet access, something often limited when working in the field, but do need a local network from which to access the necessary web

[7] https://ark.lparchaeology.com/about/ [8] Described in Tasić 2017a

technologies. There are benefits and drawbacks to any of the recording solutions projects choose to use. On the one hand, applications like FileMaker may be limited in the amount of customisation possible but there is technical support in case of issues. On the other hand, free and open-source software (FOSS) allows greater flexibility at less or no cost (Edwards and Wilson 2015; Ducke 2012), but maintenance can become an issue if there is no dedicated 'tech person' on staff. Open-source programs also increase the possibilities for reproducing research and avoid relying on institutional software choices and licenses (Ducke 2015).

Early examples of born-digital recording often occurred in large, well-funded projects around the Mediterranean (see Walldrodt 2016). As the technologies became more easily accessible, the use of mobile devices and field laptop computers varied from project to project. Some chose to make use of tablets to enhance specific aspects of excavation recording like field notebooks (Gordon et al. 2016), while others moved to a more integrative approach to data collection, management, and access (Motz and Carrier 2013; Motz 2016). Excavation projects have taken this approach to another level by integrating mobile context recording in the form of field notes and forms directly into database structures, while also integrating other forms of born-digital field recording techniques like computational photogrammetry (López et al. 2016; Roosevelt et al. 2015; Sikora and Kittel 2018). The aim of these approaches is to completely connect all data collected from the field. Digital data collection on mobile devices helps with this by standardising data collection in the form of integrated databases and providing efficient connections to other types of data. In theory, mobile field recording helps not only with efficiency in data collection but enhances the usability of those data out of the field. However, as discussed in Section 2.3, efficiency in data collection raises many questions about archaeological epistemology and the future envisioned for the discipline.

2.2 Recording in Three Dimensions

The use of three-dimensional recording technology, such as laser scanners and computational photogrammetry, has become increasingly common in archaeology over the last decade for the documentation of sites and landscapes. Range-based systems, such as laser scanners or structure light scanners, rely on the capture of absolute surface geometry, whereas image-based systems, such as computational photogrammetry, create relative spatial distances on the model (Remondino and El-Hakim 2006). Laser scanning refers to 'any technology which accurately and repeatedly measures distance, based on a precise measurement of time, and aggregates these measurements into a collection of coordinates' (Opitz 2013, 13). Airborne laser scanning (ALS), often used interchangeably with the term LiDAR (Light Detection And Ranging), began to grow in prominence beginning in the early 2000s as a result of innovations in equipment, data processing, software, and GPS technologies that significantly lowered the costs of these approaches (Opitz 2013). The two most common methods that laser scanners employ to measure distance either record the time it takes for a laser pulse to return to the instrument that emitted it (Time of Flight [TOF]) or calculate distance from the instrument by measuring the phase shift between the emitted and received continuous laser beam (Phase Shift Scanner). Most ALS scanners use TOF technology for recording their calculations (Bennett 2014; Opitz 2013). Terrestrial laser scanners (TLS) began to be used in archaeology around the same time as ALS systems, focused on the site, feature, and object-level documentation (Lercari 2016).

The amount and pace at which these surveying techniques have taken hold in archaeology cannot be understated. Entire countries in Europe now have complete LiDAR coverage, and often these governmental survey data are freely available. Slovenia, for example, has 3D landscape data available for the whole nation. The benefits of ALS for archaeological and topographic survey and remote sensing are obvious; large swaths of landscapes can be surveyed, it provides the ability to visualise features without the hinderance of vegetation, and the high resolution provided by laser scanning has truly opened new worlds for archaeology. But we can also see the benefit that this technique brings to conceptualisations of landscape, especially as it relates to the archaeological record (Mlekuž 2013; Risbøl 2013). LiDAR-derived data provides an opportunity for sites and archaeological features to be viewed as parts of the wider topographic and archaeological landscape rather than as discrete entities. And although this is not an approach unique to ALS, the seemingly straightforward visualisations that are created with these data emphasise the usefulness of this conceptualisation of landscape.

A recent example of the potential for ALS to reimagine an archaeological landscape is the examination of an Iron Age hillfort landscape around Knežak, Slovenia, by Laharnar et al. (2019). The application of ALS-derived data, through a data-specific processing approach, illuminated the complex spatial and temporal landscape of this region. Using these data, the authors were able to identify groups of cairnfields, linear earthworks, enclosures, and hollow ways that were possibly built and used largely contemporaneously as the hillforts (Figure 1). These newly identified features demonstrate that thinking of sites as discrete entities restricts possible reconstructions; the linear earthworks identified through ALS possibly acted as boundaries between hillforts, and pathways extended out from the hillfort at Gradišče above Knežak to create an intra- and

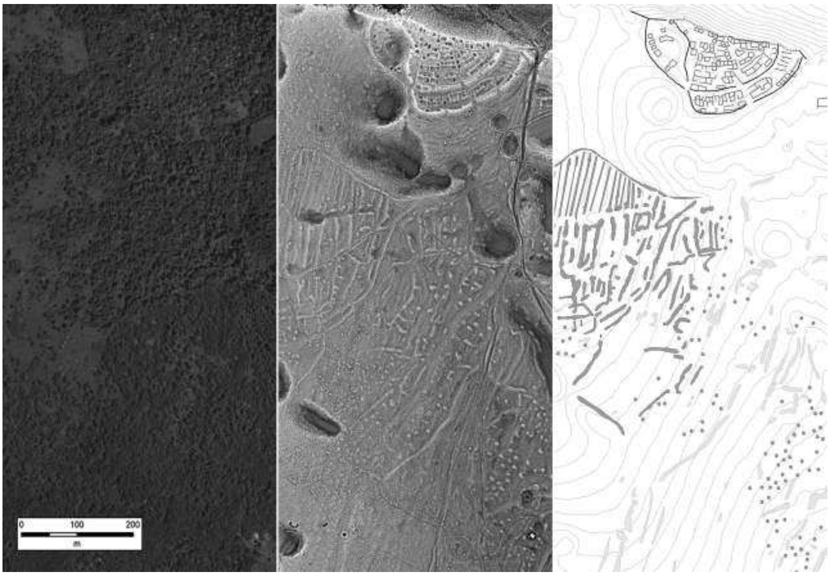

Figure 1 Gradišče above Knežak, Slovenian Iron Age hillfort. Left: aerial photography. Centre: visualisation of processed airborne LiDAR data. Right: the archaeological interpretation. Only the hillfort ramparts (black) were known before airborne LiDAR data was analysed. (Created by Edisa Lozić)

inter-site network (Laharnar et al. 2019, 252). The proper utilisation of ALS-derived data opens new possibilities to reimagine landscape and prehistoric lifeways, as this project demonstrates.

The robustness and durability of these 3D data are also demonstrated by the continuous discovery and reusability of long-running projects. Corns and Shaw (2013) outlined a broad endeavour in Ireland, funded by a combination the National Monuments Service and the Heritage Council, to capture high-resolution 3D survey data for two UNESCO World Heritage Sites and two significant royal sites. Parts of the processed data from these projects can still be viewed online.[9] And although the data derived from these ALS projects have provided enticing and publicly engaging relief-shaded DSMs,[10] the most interesting aspect of an otherwise standard (albeit wide-ranging) 3D landscape project is the length of time that the data continue to be used for new research discoveries. A good example is the particularly robust dataset created for the Brú na Boinne landscape. New discoveries and reinterpretations of the ALS data continue to be made even though the data were captured more than

[9] https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=b7c4b0e763964070ad69bf8c1572c9f5
[10] Digital Surface Model.