Title
Computer Applications in Archaeology

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Abstract
Computer applications in archaeology have been a feature of archaeology for over 50 years. From the 1950s into the 1980s they were closely associated with quantitative methods, but since then, the increasing availability and capability of personal computers has seen a dramatic growth in use. Beyond standard office software, key application areas in archaeology include databases, geographical information systems, and data visualization. The expansion of the Internet and the world-wide web has seen the development of new means of communicating archaeological information, such as the provision of access to online data and data archives.

Keywords
computer, data, digital, internet, GIS, visualization, quantification

Main Text

A key transformation in archaeology over the past fifty years has been the shift from analogue to digital. In 1953, Albert Spaulding was one of the first to highlight the potential use of mechanised and electronic methods of processing archaeological data as a means of handling the variety and quantity of data required for statistical analysis (Spaulding 1953). In 1955, Jean-Claude Gardin and Jean Deshayes implemented an optical coincidence punch card system, which captured and sorted observations relating to 4000 Bronze Age metal tools. Two sets of cards were implemented. In the first set, each card related to a single tool with a matrix of punched and un-punched holes describing the presence or absence of the different features of that tool. In the second set, each card related to a distinctive feature, and the punched holes indicated which tools exhibited that feature (Gardin 1958). Subsequently, in 1959, Gardin and Peter Ihm implemented what is generally accepted to be the first example of a computer application within archaeology, using it to automatically classify the collection of Bronze Age tools (Cowgill 1967). In the USA, James Deetz is credited with earliest use of computer-based processing in 1960, performing a cluster analysis of design elements in Arikara ceramics (Cowgill 1967).

These early applications of computers in archaeology display two aspects which have coloured approaches through to the present day: issues surrounding the description and classification of archaeological objects, and the use of statistical techniques. These were inextricably linked in a concern with the need to capture the richness and complexity of archaeological data within numerical recording systems in order to facilitate computer-based classification and analysis. Typically, this entailed the definition of a set of descriptive traits along with predefined values for each state, involving the atomisation of data and the selection of characteristics which are seen to be relevant. These numerical codes for the differential states of material objects were then considered amenable to quantitative analysis employing techniques such as automated sorting, classification, and a range of multivariate numerical methodologies.

The creation of a computer representation or digital model of the data necessarily meant that analysis was predicated upon the entities being capable of representation within the digital model – anything that could not be captured digitally could not be incorporated within the model and subsequently within the analysis. Indeed, the construction of the digital data model was seen to entail a highly reductionist approach in which the complexity of the archaeological data was deconstructed into simpler, more basic entities capable of being modelled. This found resonance in the processual or 'new' archaeology of the 1960s, in which a more 'scientific' approach was closely associated with hypothesis-testing, quantification, statistical techniques, and consequently computer applications. As a result, for much of their history computer applications in archaeology have been closely associated with formal, 'scientific', processual approaches to archaeology, and computerisation frequently came to imply quantification (Doran and Hodson 1975).

This highlights a significant tension that has existed within computer applications in archaeology: their association with quantitative rather than qualitative data. The scientific goals and methodologies commonly linked with computers, requiring precision and algorithmic clarity, did not sit comfortably with the more humanistic approaches related with post-processual or interpretive methods developed by archaeologists in the 1970s and 1980s in response to the 'new' archaeology. Consequently, the introduction of new computer applications such as Geographic Information Systems in the 1980s, were perceived in some quarters as being founded upon old, discredited theoretical positions because of their apparent reliance on environmental and other non-qualitative data coupled with their use of quantitative methods.

Key application areas

The growth in computer power and storage capacity alongside its physical reduction from room-scale to desktop and portable equipment associated with the microcomputer revolution of the 1980s is arguably the most transformational development in terms of computer applications in archaeology, continuing through to the present day with developments in hand-held and wearable computers. Increased access to and availability of computer hardware and software meant that most archaeologists, in common with specialists in other disciplines, increasingly turned to computers for their day-to-day work. Word processors, spreadsheets, graphics programs, and databases became embedded in archaeological practice. At the same time, the growth in computer usage in archaeology saw a decline in the emphasis on quantitative methods and an increased focus on the production of texts as part of daily professional practice. In the process, most computer applications in archaeology became reliant on off-the-shelf software: as computers became more pervasive, fewer bespoke archaeological programs were required to meet the demands of the subject. Apart from highly specialised areas such as aerial photograph rectification, geophysical survey, and radiocarbon calibration, most archaeological tasks could be undertaken using widely available commercial packages, and, increasingly in recent years, free open source software. A consequence of this was that by the 1990s, archaeological computing could be seen as essentially in a subordinate relationship with other disciplines such as information science, image processing, computer vision, and geographical science, with little novel development taking place within archaeology beyond the application itself. This might be interpreted as evidence of the maturity and ubiquity of computer applications within archaeology or alternatively as a lack of creativity or ambition.

Other than specialised software for highly restricted archaeological tasks, the main computer application types include database management systems (DBMS), geographical information systems (GIS), and visualisation systems, with less commonplace being artificial intelligence/expert systems, simulation systems, agent-based modelling, and the continued use of statistical software. These find application across the discipline in areas such as field survey and prospection, excavation recording, post-excavation analysis, local and regional landscape analysis, and cultural resource management. Beyond details of their specific implementation, debates surrounding these applications generally focus on the structuring of data within the various systems and the analysis and visualisation of those data in support of the interpretation of the past.

Recording data

From the outset, the preparation of data for computer applications has entailed a process of abstraction: the identification and selection of the entities of interest which are to be represented within the data structures. For example, early archaeological databases, including many regional sites and monuments inventories, were typically implemented in a simple flat-file structure in which data were recorded in a two-dimensional matrix where each entity was represented by a row (record), and their defined attributes by the columns (fields). Archaeologists subsequently embraced the relational database management system which was capable of modelling the relationships between the different archaeological entities as a series of interlinked flat-file tables, and in the process, reducing the redundancy common in the single flat-file database and simplifying data retrieval by removing the need to search through multiple identical data fields. For instance, a flat-file system would require as many columns as necessary to record the maximum number of artefacts found within a grave, whether or not it actually had any, whereas in a relational system a single grave record in one table would be linked to its accompanying artefacts (if any) in a second table. The abstraction typically required to structure data took complex entities and simplified them in order to capture them, and in the process focused on certain characteristics while discarding others. Since this has implications for the comparability and reusability of the data by others at a later stage, attempts were made to enforce standards in the definition and recording of data, either by seeking to impose standard software systems or by requiring the use of standardised terminology through the provision of wordlists or more complex thesauri. Inevitably this was resisted in some quarters as a restriction on practice and placing limits on research but, if anything, the standardisation of terminology has assumed a more significant role as data have moved onto the Internet with the potential to be accessed across national and international boundaries although in this context these standards are commonly applied to data in a post-hoc manner.

Spatial data

Geographical Information Systems (GIS) were first used in the USA and only saw wider adoption in Europe later in the mid-1990s. The attraction of GIS was the way in which they could incorporate descriptive data with spatial information and provide an accessible integrated system capable of spatially linking multiple data sources: data tables, digital maps and plans, topographic data, geophysical survey data, georeferenced aerial photographs and satellite imagery, hydrology, soils, and a host of other environmental data, for example. Once incorporated, GIS provided a range of tools capable of performing quite complex analyses on the data in a relatively straightforward manner and characteristically generating visual results. Classically, GIS were employed in different ways in the USA and Europe. In the USA, there was a focus on cultural resource management, including predictive modelling to determine the likelihood of encountering sites. In contrast, in Europe the focus was more specifically linked with landscape modelling within a theoretical context to investigate aspects such as movement, visibility, prominence and proximity. Although these distinctions have broken down with the passing of time and GIS applications have extended into intra-site and excavation recording systems, it remains the case that predictive modelling for cultural resource management applications has not been widely used in Europe and, where it has been applied in the Netherlands, it has since been criticised for its unreliable results (Kamermans 2007). In terms of data structuring, a recurring issue with GIS is ironically its spatial determinism: unless an entity can be described in terms of a point, line, polygon, or a set of raster values, it cannot be represented within a GIS data model. This enhanced the perception of

GIS as a positivist tool, rooted in processual archaeology, and largely incapable of incorporating cultural and social variables. The resurgence of statistical tests of association and spatial analytical techniques within GIS served to reinforce the view that GIS harked back to an earlier theoretical milieu. Although GIS remain a powerful data management and visualisation tool regardless, considerable efforts have been expended in attempts to integrate post-processual landscape analyses employing humanistic, cognitive and cultural variables within the GIS model. This is frequently achieved through the use of proxies – for instance, visibility standing for perception and knowledge of a place – or through the introduction of new tools and procedures for representing movement and vision, for example, although these are often not available within standard GIS packages.

Visualising data

Visualisation, and especially 3D modelling, has seen a significant growth in use in conjunction with the increased availability of fast computers and powerful software. The earliest examples of 'virtual archaeology' were produced using mainframe computers and highly specialised software. The incorporation of tools within computer-aided design (CAD) programs made 3D modelling more accessible, although the architectural and engineering origins of the software tended to mean that reconstruction models were frequently of buildings and often classical in nature. Reconstructions tended to be static views, divorced from their surrounding landscape, and lacking any human dimension. The development of 3D animation software and, more recently, the availability of computer gaming environments and their associated assets facilitated the expansion of archaeological reconstructions into much more ambitious interactive virtual environments, with natural features, textures, vegetation, objects, people, and animals. The increased reliance on computer-generated imagery (CGI) in films and the immersive qualities of computer games has raised expectations of realism and this has created challenges for archaeological reconstruction. In particular, a focus on realistic representation sits uncomfortably with the levels of archaeological interpretation involved in reconstruction – for example, frequently a structure may consist of no more than foundations so that everything reconstructed above ground is based on interpretation and imagination. It has long been accepted that a computer model carries with it connotations of authority, and the degree of realism achieved is often linked to the perceived level of authenticity represented by the model. Communicating uncertainty and the presence of interpretative elements within the same model whilst retaining the desire for realism is problematic, and approaches generally rely on accompanying documentation or paradata which describes the decision-making process and the construction pipeline used.

Internet archaeology

In concert with wider society, archaeology has embraced the growth of the Internet, and specifically the World Wide Web, since the mid-1990s and in many respects this has come to underpin computer applications within archaeology. Although initially focused on the creation of websites and indices to web sites, increasing access to the web triggered developments in a number of directions. The reliance of the World Wide Web on hypertext markup language (HTML) encouraged exploration of hypertext which was seen to provide a means of publication suited to a post-processual view of the past by virtue of its subversion of traditional print text paradigms through its perceived erosion of authorship and empowerment of the reader, and the way it enabled interactivity, multivocality, and reflexivity in its texts. However, reality fell far short of vision: the author has remained paramount and the reader subject to the connections created by the author. Contrary to expectation, text is not being decomposed into chunks and massively interlinked; instead, very conventional whole documents, with much of their structure and paper origins clearly apparent, are loosely linked together. As a result, divisions between author and reader, producer and consumer, have been technologically reinforced. Indeed, with some exceptions (such as the online journal *Internet Archaeology*) the growth of web-based archaeological publications is largely reliant on delivering text and images in fixed traditional print layouts such as provided through the Portable Document Format (PDF).

The Internet has been increasingly employed to provide access to archaeological information to a wider audience. Searchable datasets such as national and local heritage records, providing information about site location, period, and events, and typically provided by national and regional heritage agencies, have transformed approaches to desk-based studies in countries such as the UK, Netherlands, and Germany. Downloadable datasets, associated with excavations, surveys, and other archaeological interventions, have also become progressively available in the UK, USA, Netherlands, and Germany, with new digital repositories also being established elsewhere. Coupled with this, considerable attention has been paid to the existence of large bodies of archaeological data captured within traditional published journals and in ‘grey literature’ unpublished reports, and means sought to extract relevant information automatically from their PDFs using natural language processing techniques. At a relatively early stage, this draws upon earlier standards work and aspects of artificial intelligence in order to construct ontologies: structured syntaxes for describing and capturing the concepts and contexts of information and the relationships between them. These provide a means for establishing interoperability between disparate datasets and constitute the ‘linked data’ which underpins the creation of the Semantic Web. Aligning datasets collected by different people at different times and in different places is challenging, and furthermore sits somewhat awkwardly with a situated and contingent view of archaeological information, but the benefits of linking and sharing data are beginning to be demonstrated through large-scale synthetic analyses which would be difficult if not impossible to achieve in their absence.

Making data available in these ways and facilitating their reuse is seen as a key means of ensuring their survival, and this principle underpins archaeological digital archives such as those provided by the Archaeology Data Service (UK), tDAR (USA), and Open Context (USA). Most professional codes of ethics require archiving of digital data, but there remains a degree of dislocation between the funding models of these archives and their role as suppliers of data of record: for the most part funding is insecure, dependent on grant aid or the generation of commercial income. While it is possible to demonstrate the value of these resources in financial terms, this is primarily associated with the benefits of access to online indices and inventories for commercial desk-based analyses, whereas the value of the reuse of archived primary data has proved harder to demonstrate despite its perceived importance amongst the archaeological community. With national governments promoting open access to data, heritage agencies are perhaps in a stronger position to support access to data, but again this largely relates to the provision of management inventories rather than primary datasets.

Computing futures

Predicting the future directions of computer applications in archaeology is unlikely to be successful; however, a number of characteristics can be identified. A continued reliance on applications developed in other fields for different purposes may be anticipated, together with the benefits which might accrue – for example, the recent demonstrations of the value of publicly available satellite imagery in the discovery of new sites and tracking the damage inflicted on known sites within conflict areas. The disparate nature of archaeological data, with its variety, complexity, spatial, and temporal dimensions, will continue to be an attraction for the development of linked data and natural language processing. There is also the way in which tools and techniques which may not initially be transformative can subsequently re-emerge in new areas: for instance, artificial intelligence techniques and expert systems never took off in a significant way in the 1980s but are integral to developments associated with automated data processing and ‘big data’ analysis. Visualisation of archaeological data is clearly an area of future growth, and it might be anticipated that it will expand in new directions – for instance, linking gaming engines and their environments with agent-based modelling, and there is the imminent challenge of virtual reality and augmented reality. In a field that is constantly changing, one thing is certain: that computer applications in archaeology will develop in exciting and unpredictable ways.

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