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Getting the Best Fit? 25 Years of Statistical Techniques in Archaeology

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Abstract - *The paper catalogues the first 25 years of CAA contributions, from diverse authors, institutions and countries, to statistical techniques in archaeology, including data analysis, Numerical Taxonomy, Similarity Studies, Factor Analysis, Principal Components Analysis, Correspondence Analysis, Multivariate Statistics, Matrix analysis, Regression, Pottery Quantification, Shape Coding, Cluster Analysis, Seriation, Multidimensional Scaling, Correlation of dating measurements, Simulation, Computer Modelling and archaeological theory, Expert Systems, Artificial Intelligence, Stratigraphical Analysis, Spatial Analysis and Geographical Information Systems. The introduction briefly covers seminal achievements to the discipline of computing archaeology before the advent of CAA in 1973.*

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1 Introduction

1.1 Early days

Irwin Scollar (1982) in his address entitled "Thirty years of computer archaeology and the future" started out by saying that the title was wrong, and that it should really read something like "25 or so years", and yet in 1997 CAA97 celebrated 25 years of Computer Applications and Quantitative Methods in Archaeology in the meetings of CAA since 1973. Obviously this points out that all was not darkness on the face of the earth before CAA, so we should begin by exploring the seminal work which was undertaken in archaeological applications of computers since the machines became available for such research in the late 1940s and early 1950s.

1.2 Late 1950s, 1960s

These were the days of mainframe computers, electronic valves and early transistor machines, regarded primarily as calculating engines. Much of the work concerned mathematical and statistical techniques applied to archaeological data. Techniques had however been developed in a pencil-and-paper fashion before the advent of computers, examples being the "Sequence Dating" (matrix ordering, seriation) of Flinders Petrie (1899) involving the ordering of Egyptian pre-Dynastic pottery records written on slips of paper, which was later adopted for Zuñi pottery classification in the USA (Kroeber 1916), and various matrix ordering and minimum spanning tree derivation methods.

1.3 Main strands in computing archaeology

There have been in general three different categories of problem, with three different corresponding groups of workers involved in computing archaeology from the beginning. The first group was mathematicians and statisticians. In the late 1950s and early 1960s the first and second generation computers were regarded primarily as calculating engines. Much of the work concerned mathematical and statistical techniques applied to archaeological data. The paper on seriation by Robinson (1951) can be regarded as the beginning of the seriation class of numerical methods in archaeology. In this we have the first example of "hunting in pairs", where Brainerd and Robinson each contributed their expertise to a joint project. In the UK, data analysis methods became popular in archaeology from about 1966, following the availability of a standard work by Sokal and Sneath (1963). Numerical taxonomy was likewise encouraged by papers by Hodson, Sneath and Doran (1966) and Doran and Hodson (1966), and factor analysis by Binford and Binford (1966). Cultural pattern studies employed factor analysis Binford and Binford (1966). Multidimensional Scaling Doran and Hodson (1966), Principal Components Analysis (Hodson 1969), Canonical Analysis (Graham 1970), and Constellation Analysis (Azoury & Hodson 1973). In France, at the laboratory for mathematical statistics at the University of Paris VI, Escofier (1969) developed Correspondence Analysis.

The second group of people consisted of scientists and engineers concerned with scientific data from prospection measurements (resistivity meter, proton gradiometer) made on archaeological sites, and from chemical and emission analyses made on artefacts for composition or dating. It is not surprising that scientists, engineers, mathematicians and statisticians were first in the field, for they had early access to first and second generation computers.

The third group of people were museum people who may or may not have been archaeologists. According to Cowgill (1967a; 1967b; 1968); site data was first put into a computer in about 1959 by Ihm (1961) and Gardin. Gardin claims that this 1959 work, on the Euratom IBM 650 at Ispra, Italy, on a collection of Eurasian Bronze Age axes, was the first use of statistical techniques in archaeology using a computer. Early computers had little memory, so the the first implementations of databanks are heavily concerned with data coding and compression. Early databanks were also set up in the early 1960s for excavation and museum catalogues.

Archaeologists really got involved much later (late 1970s, early 1980s) when they could afford personal microcomputers. This review paper will be confined to comments on the quantitative methods of data analysis used for processing data about archaeological entities: Numerical Taxonomy, Similarity Studies, Factor Analysis, Principal Components Analysis, Correspondence Analysis, Multivariate Statistics, Matrix analysis, Regression, Pottery Quantification, Shape Coding, Cluster Analysis, Seriation, Multidimensional Scaling, Correlation of dating measurements, Simulation, Computer Modelling and archaeological theory, Expert Systems, Artificial Intelligence, Stratigraphical Analysis, Spatial Analysis and Geographical Information Systems. Developments in all areas have been hardware and software driven by progress in computers and computing (processor speed, memory size, operating systems and high-level languages) outside the archaeological field.

1.4 Early conferences

Conferences with some content of mathematics and statistics applied to archaeology before the inception of CAA included:

1950 New York (Brainerd 1951)

1959 Burg Wartenstein (Spaulding 1960)

1963 Moscow (Koltchin 1965)

1966 Rome (Centre National de la Recherche Scientifique 1968)

1968 New York (Metropolitan Museum of Art 1968)

1969 Marseilles (Gardin and Richaud (eds.) 1970)

1970 Mamaia (Hodson, Kendall and Tautu 1971; Wilcock 1970; Hodson and Kendall 1971)

1971 Sheffield (Renfrew 1973)

1971 Marseilles (Kendall 1974)

The 1970 Mamaia conference covered the subject areas Typology & Taxonomy, Seriation — including Petrifaction, Kendall's HORSHU and *Operation Speckled Band* (an unbending of the "horseshoe" configuration common in seriations shown on multidimensional scaling scalograms, being a literary reference to Conan Doyle's Sherlock Holmes novel *The Speckled Band*), Population Genetics & Historical Demography, "Unusual Applications" — Mosaic analysis, databases, geophysics, graphics, and excavation data capture, showing that these last topics were in their infancy, Linkage and Multidimensional Scaling, and "New Techniques" — glottochronology, comparison of multivariate analyses, cemetery analysis, and pottery shape analysis. Around this time Principal Components Analysis replaced Factor Analysis, which was really never applied in archaeology, and Multidimensional Scaling appeared, only to go out of favour in modern computing archaeology.

In the following bibliographies, seminal works, both books and papers, are given up to 1973. Although there are many books on computing archaeological topics and papers published outside CAA, dated 1974 or later, these are not given below, since the purpose of this paper is to review the achievements of CAA only, against the background of earlier work. The coverage is up to and including CAA95.

2 Data analysis, numerical taxonomy, similarity studies, factor analysis, principal components analysis, correspondence analysis, multivariate statistics, matrix analysis, regression, pottery quantification, shape coding and cluster analysis

Numerical taxonomy as applied to archaeology concerns the attachment of numerical quantities to certain attributes of archaeological materials, whereby the description of the materials may be made more objective. By calculating suitable similarity coefficients between pairs of objects based on these numerical quantities a typology may be constructed which is based solely on the population.

The subject stands on the broad-based theory of statistics developed over the past 75 years. An important early paper by Mahalanobis (1936) gives the definition of the generalised distance coefficient between species and sub-species, based on pooled variance and covariance. The increasing availability of computers made numerical taxonomy more popular, and this increased interest was reflected in papers by Sneath and Sokal (1962) and Sokal and Sneath (1963). These works defined taxonomic terms, with reference to biological data. The most important techniques for archaeologists are seriation, phenon diagrams (dendrograms), similarity coefficients and taxonomic distance. A research seminar on statistics and archaeology held at the Institute of Archaeology, London on 30 May 1964 reflected the increasing interest among archaeologists, and a relevant paper was that by Roe on the metrical and statistical analysis of hand-axe groups, published in more detail in 1968.

In the USA Brown and Freeman (1964) used regression in the study of sherd frequencies from the Carter Ranch Pueblo, using a UNIVAC computer, Binford and Binford (1966) carried out an analysis of Mousterian artefacts, and Cowgill (1968) investigated the advantages and limitations of multidimensional scaling, factor analysis and cluster analysis, discussing his own work and the results of Hodson, Binford, and Brown and Freeman.

There has been a lively debate over the validity of polythetic agglomerative, monothetic divisive, single-link, multiple-link and average-link clustering methodologies. In 1965 there appeared the first of a series of papers concerning clustering methods, which aroused a controversy which has continued to the present. The protagonists were a Cambridge group (Jardine, Jardine and Sibson) and a group from Australia (Lance Williams, Clifford and Dale); the controversy concerned clustering methods, automatic classification, taxonomic hierarchies and the rigour of the associated mathematics, or lack of it. Much of the controversy can be attributed to different linguistic usage, but in the remaining differences probably both schools had something to offer. It seems pointless to adhere blindly to rigorous mathematical arguments about single-link clustering being the only valid procedure, when average-link clustering gives sensible and useful results in many archaeological applications. On the other hand, the proliferation of methods without adequate theoretical background leaves the archaeologist in some doubt as to which to use, and perhaps leads to a subjective choice of algorithm which the automatic classification methods were originally constructed to avoid.

Most of the methods are based on storage of the data in matrix or half-matrix form, the items vs. properties incidence matrix leading to the Q-type item vs. item square matrix comparing items, and the R-type property vs. property square matrix comparing the performance of properties. The incidence and square matrices may be manipulated by re-ordering columns and rows to give linear seriations, and minimum spanning trees may also be derived. The property vs. property square matrix is also the starting point for Principal Components Analysis.

One of the earliest applications of matrix ordering in Britain (to British Beaker pottery) was by Clarke (1963), the first of many books and papers produced by this author before his untimely death.

The Cumulative Percentage Graph and its application was described by Doran and Hodson (1966), Kerrich and Clarke (1967) and Whallon (1972).

Several manual methods have been developed, whereby small sets of data may be analysed without the use of a computer. The methods re-order matrices to produce linear seriations (Gelfand 1971), or take the two highest links from each column, followed by deletion of the weakest links in each loop, to produce the minimum spanning tree (Renfrew and Sterud 1969).

Data analysis has received the largest coverage in the literature, perhaps because of its theoretical appeal, and because it is less labour-intensive than data recording from instruments or creating databases. The simplest applications in this field for computers are the generation of descriptive statistics and the manipulation of quantities of data too large to be managed by hand. The routine production of basic descriptive statistics, diagrams and charts is now commonplace, providing the starting point for more complex analytical studies.

Data analysis is the dominant activity in archaeology, and classification comes a close second. Their extension into computing has led to a variety of methods largely developed from the biological sciences. Cluster Analysis is the core of the computerised classification procedures, but the methods are linked to many other areas such as Factor Analysis, Principal Components Analysis and Correspondence Analysis. These methods have become possible only through use of the computer.

The early applications of data analysis were often tackled by archaeologists and statisticians "hunting in pairs", problems of type coding being left to the archaeologists to do by hand, and the statisticians calculating similarity values and re-ordering matrices in order to seriate or classify the data.

In data analysis most attention has been paid to procedures for classifying, ordering (in terms of time or evolution) and grouping artefacts, assemblages or sites (Similarity Coefficients, Shape Analysis, Cluster Analysis, Seriation), procedures for discovering "factors" or dominant characteristics (Principal Components, Multidimensional Scaling, Multidimensional matrix ordering), and procedures for discovering geographical or spatial relationships (Curve Fitting, Pattern Recognition, Nearest Neighbour Analysis, Chi-Squared, Pearson's Contingency Coefficient, Local Density Analysis, Trend Surface Analysis, etc.).

Thus it was that the mathematical clustering algorithms which appeared in the 1950s and 1960s for biology and biometrics were readily adapted for use in archaeology (Hodson, Sneath & Doran 1966; Doran 1967). Since the early 1970s well-known and reliable packages such as CLUSTAN and SPSS have reduced the problems of data analysis for the archaeologist. The use of well-tested packages is to be encouraged, since this reduces the need for programming, but archaeologists should not use the algorithms uncritically and should understand the statistical limitations of the methods and when they should or should not be used. The "results" will depend very much on the algorithm used, and this is not well understood by some archaeologists — there will always be an "answer" but is it the correct answer? In the early days the algorithms were severely restricted in matrix size by the amount of memory available, and outputs were restricted to line printer. The improved memory space and cheap colour graphics available in modern desk-top computers has revolutionised the presentation of clustering and classification results. The use of well-tested packages is to be encouraged, since users may then concentrate on matters of data selection, entry and validation rather than on programming. However, what may then be supposed to be an objective procedure because a computer is being used, is subjective in the sense that different results are obtained from different algorithms, a point little understood by some archaeologists.

English language workers often ignore the significant contributions which have been made by the French (summarised by Djindjian 1989). Several statistics laboratories in France contributed to a quantitative movement known as 'the French School of Data Analysis'. The chief contributions were numerous multivariate analysis methods, Correspondence Analysis, and cluster analysis algorithms (Typological Analysis, Morphological Analysis, culture pattern studies, provenance studies).

3 Seriation, multidimensional scaling, correlation of dating measurements

Seriation received attention first because there were in existence well-known manual methods for matrix ordering and minimum spanning tree linkage long before computers became generally available. The first notable "hunting in pairs" team was Brainerd and Robinson (Brainerd 1951). Belous (1953) applied the new seriation ideas to the Central California chronological sequence, while Ascher (1959) used a three-pole plot to illustrate seriation. Ascher and Ascher (1963) developed the first computer program for the ordering of matrices after the method of Brainerd and Robinson, and Dempsey and Baumhoff (1963) extended the seriation method to presence/absence data.

The first computer program for Multidimensional Scaling was designed by Shepard (1962), with the support of Kruskal (1964a; 1964b), and the method was further developed by Kendall (1963; 1969a; 1969b ;1970; 1971a; 1971b) from the work of Flinders Petrie (1899). Kendall's 1971a paper introduced a multidimensional scaling algorithm modified by a circular product transformation, the HORSHU method (see above in the description of the 1970 Mamaia conference) developed by Wilkinson (the "circle-up" method of unbending the horseshoe).

One of the simplest and fastest algorithms for seriation was developed by Goldmann, an archaeologist and Kammerer, a programmer (Goldmann 1968; 1972). Interest in seriation increased through the early and mid 1970s, since when little new has appeared.

Hodson (1968) and Hodson (1969) worked on a collection of La Tène brooches from a linear cemetery at Münsingen-Rain, using average-link cluster analysis, principal components analysis and multidimensional scaling. Hodson, Sneath and Doran (1966) particularly discussed the Münsingen-Rain application. Hodson (1970) later developed the k-means cluster analysis method.

Seriation is one of the extremely few quantitative analytical methods which can be said to have been developed by archaeologists strictly for archaeological application. In importance in the field of archaeological problems it can probably be said to be third (with data analysis first and classification second). In the late 1960s, however, there was an explosion of methodology which was not led by archaeologists, but rather by mathematicians and statisticians. The problem of seriation was attacked theoretically, leading to a variety of methods which archaeologists must now choose between. Multidimensional Scaling, very popular in the late 1960s and early 1970s, has links with seriation if one reads around the 'horseshoe' on a scalogram, but the method has gone out of favour in the 1990s.

4 Simulation, computer modelling and archaeological theory

Ideas and approaches derived from the world of computers have had a significant impact on archaeological thought and method. The introduction of computer processing has influenced the analysis of archaeological data by enabling more complex manipulations and statistical calculations to be done than could have been achieved in any other way. More importantly, the need for clarity and logical precision in computing has forced archaeologists into more precise ways of thinking, leading in turn to new ideas for analysis or even to reconsideration of theory. The process is cumulative, and use of a computer inevitably leads to further applications for that computer.

Simulation is one of the newer and less important computer applications in archaeology. The approach offers an attractive approach to model building, linked to systems theory. An archaeological explanation becomes a matter of defining the variables and actors in a population or culture, and of defining the relationships and interactions between these variables and actors. The main obstacles have been the difficulty of estimating the size of parameters for a hypothetical system from the available archaeological data, and thereafter the difficulty of checking the validity of the results of the simulation against what actually happened in archaeological time.

Chenhall (1966) and Chenhall (1968) discussed the logic of models, and Cowgill Cowgill (1967a) , Cowgill (1967b) and Cowgill (1968) was instrumental in introducing the SYMAP software for mapping, using it to interpret the urbanisation of Teotihuacan, Mexico, on the basis of detailed mapping, surface reconnaissance and selected excavations.

The first of many papers by Doran (1967a), formerly a member of the Department of Machine Intelligence and Perception, Edinburgh, put forward a computer scientist's viewpoint on the use of computers in archaeology. Further papers (1967b; 1970; 1971a; 1972) described the development of general machine intelligence concepts applied to archaeology. The papers explore systems theory and computer simulations applied to archaeology, evaluating attempts by Clarke and others to make use of concepts drawn from systems theory and cybernetics, and also comparing archaeological reasoning and machine reasoning. The 1971 paper described the computer analysis of the linear cemetery at Münsingen-Rain. The fibulae data consists of measurements and motifs, and the results were presented in distribution map and histogram form.

5 Expert systems and artificial intelligence

Attempts to use Expert System methodology in archaeology have largely failed because of the extremely diffuse nature of the archaeological situation. Where a modicum of success has been achieved, such as in the classification of teeth (Brough and Parfitt 1984), the data fields and measurements are already precisely defined in a scientific sense.

6 Stratigraphical analysis

A number of techniques for ordering archaeological contexts based on context relationships have been developed. These all sprang from the Harris Matrix type of definition of context relationships (Harris, E.C. 1975.) 'The stratigraphic sequence: a question of time', *World*

Archaeology), and the methods now provide routine tools for analysis of the relationships between excavated contexts on an archaeological site.

7 Spatial analysis and geographical information systems

Spatial analysis began with the central place theory of Christaller (1933), but geographers in general were slow to adopt quantitative methods and the use of computers.

In plant studies spatial analysis using quadrats was employed in the late 1950s and early 1960s, but the introduction of geographical co-ordinates came much later in computing archaeology, archaeological spatial analysis techniques not appearing until the late 1960s and early 1970s. The simple archaeological area plots of the mid-1960s have given way to standard mapping and contouring packages such as SYMAP, and more recently to sophisticated GIS packages. Trend Surface Analysis was applied by Sneath (1967) to distributions of various skull types.

For successful use in archaeology, spatial analysis techniques will be needed beyond those described by Hodder and Orton (Hodder, I. and C. Orton 1976. *Spatial analysis in archaeology*, Cambridge University Press, Cambridge). With the availability of larger memories, larger data sets have been manipulated through the 1980s and 1990s using Geographical Information Systems. However, although many pretty overlay pictures have been obtained by logical conjunctions of the improved data sets, there has been insufficient development in spatial simulation techniques to influence archaeological theory.

8 Commentary and conclusions

With respect to the importance of statistics and quantitative methods in computing archaeology, a study has been made of the developments reported in the published papers of the Computer Applications and Quantitative Methods in Archaeology Conferences since 1973. The further developments in computing archaeological techniques attributable to CAA are listed in the bibliographies below, and the coverage of the CAA conferences between 1973 and 1995 is comprehensive for statistical methods. The selection of seminal books and papers up to 1973 is mine alone, and no work outside CAA is listed from 1974 onwards, since the brief is to examine the contribution of CAA to the subject, within the context of earlier work.

A raw count of the number of pages published in various CAA years is shown in Fig. 1, with peaks in the two-volume publications of 1988 and 1995.

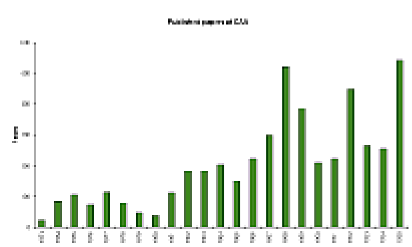

Figure 1: A graph of the raw page counts of papers published in the CAA years 1973–1995, showing peaks in the two-volume publications of 1988 and 1995.

A more enlightening summary is shown by the graph of Fig. 2, which shows the percentage importance of quantitative methods at CAA. Databases and statistics were the earlier and most important applications. Starting with a 65% emphasis on databases in 1973, a cyclic effect is detectable, databases being more important in 1973, 1982–1985 and 1989–1991, and statistics being more important in 1974–1980, 1987 and 1992. The lower statistics peaks from 1987 onwards are a consequence of more diverse areas of application being developed in later years.

Figure 2: A graph of the percentage importance of quantitative methods (QM) at CAA for the years 1973–1995, with the titles of the conferences. Statistics and QM were better represented in 1974–1980, 1987 and 1992. The lower statistics peaks from 1987 onwards are a consequence of more diverse areas of application being developed in later years.

The original title of the conferences was "Computer Applications in Archaeology" (CAA). However, the apparent decline in quantitative methods evident at the 1986 CAA Conference prompted quantitative methods workers, and particularly Bob Laxton, to propose a change in title of the Conferences to "Computer and Quantitative Methods in Archaeology", and this was accepted in 1987. In 1989 the title was changed again to "Computer Applications and Quantitative Methods in Archaeology" which it has remained ever since.

Finally, what is the health of quantitative methods in Computing Archaeology generally? 1995 shows a rising limb, and the indications are that a relative importance for quantitative methods of about 25% of all papers at CAA will be maintained. We shall see!

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