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THE GOLDEN YEARS FOR MATHEMATICS AND COMPUTERS IN ARCHAEOLOGY (1965-1985)

1. Introduction

For twenty years, from 1965 and 1985, Archaeology was the major field of application of mathematics and computers, as in other Natural, Social and Human Sciences. At the same time, applications involving Physics were also being used in Archaeology. In this paper we attempt to reconstruct the history of these twenty years, the main actors, their contribution to the evolution of Archaeology, the reason for the shift towards Computing Archaeology and the present potential comeback resulting from these techniques (Fig. 1).

2. 1945. A worldwide context for the development of scientific research

Between the two world wars, the progress of a quantitative movement in Anthropology, Sociology and Psychology also influenced other sectors of the Social and Human Sciences, in particular Archaeology. Similarly, the influence of quantification in the Earth Sciences (Geology, Taxonomy, Ecology, etc.) became very important in prehistoric Archaeology.

The researchers helping the war effort (operational research), based on fundamental research, applied the methods and tools developed during the war, promoting quantitative approaches and mathematics. The foundation and the development of large European research organizations were inspired by the model of the USSR Academy of Sciences: the CNRS in France, the CNR in Italy, and of course other institutions in all the Eastern and Central European countries located behind the iron curtain. The very large number of researchers recruited between 1945 and 1965 for those institutions augmented fundamental and applied research for the next thirty years until about 1975, when the recruitment of researchers was limited.

3. 1945-1965. The general development of a quantitative movement in Social and Human Sciences and in Archaeology: statistics and graphics without computers

During the period from 1945 to 1965, Archaeology was the field of a very dynamic quantitative movement, using elementary statistics and graphics, to solve the main classical questions that are at the origin of the methods we now use for processing archaeological data.

The names below represent a partial list of several of the main contributors from the USA and Europe:

Mielke (1949)	Cultural facies
Brainerd, Robinson (1951)	Seriation
Spaulding (1953)	Typology and statistics (χ^2)
Bordes, Bourgon (1953)	Cumulative diagram for cultural facies
Clark, Evans (1954)	Nearest Neighbour Analysis and spatial analysis
Bohmers (1956)	Graphics and statistics for typology
Meighan (1959)	Seriation
De Heinzelin (1960)	Typology and statistics
Vescelius (1960)	Sampling
Ford (1962)	Graphics for seriation
Clarke (1962)	Matrix Analysis
Vertes (1964)	Statistics and graphics
Laplace (1966)	χ^2 test and "Synthetotype" for cultural facies
Angel (1969)	Prehistoric demography

At the same time, other preliminary research works dealt with the formalization and recording of data for the purpose of archaeological data banks, using punch card machines (Gardin 1958).

4. 1960. The computer liberates the researcher from manual computing

After the laboratory experimental machines (1946-1950), the first products appeared in the 1950s: 1951, Univac 1 (Remington Rand); 1952, Gamma 2 (Machines Bull); 1952, IBM 701 (IBM). In 1955, the Fortran language was developed on the IBM 704, the first scientific computer. The first business computer, IBM 1401, developed in 1959, was followed in 1964 by the IBM 360, the first of the fully compatible upgraded IBM machines.

Starting in 1960, the first computers for academic research were installed in computer centres of the universities for general purposes. It was a heroic time for researchers who were obliged to develop their own software in binary language, assembly language and then Fortran language for scientific programs. Fortunately, the computer departments in the universities started to develop the first packages, offering users the first statistical software (SPSS, Osiris, BMDP). Not just limited to elementary statistics, statistical tests or graphics, the packages were also offering tools to develop sophisticated algorithms like numerical taxonomy (Sneath 1957; Sokal, Sneath 1963), Factor Analysis, Quantitative Geography (Haggett 1965). At the same time, it was also the very beginning of mapping (Bertin 1967, Sémiologie graphique) and maps were printed by special dedicated machines ("traceurs") until the end of the 1970s.

5. Many other scientific influences

During this period, many other types of research influenced the fields of the Human and Social Sciences, for example:

– System dynamics of J.W. Forrester: 1961 (Industrial dynamics), 1969 (Urban dynamics), 1971 (World dynamics). It is interesting to note the relationships with the disputed 1972 "Limits to growth" of the club of Rome, recently updated in 2004.
– Mathematical Ecology (Pielou 1969);
– Catastrophe theory (Thom 1972);
– Mathematical modeling including Multi-agent system (Doran 1981);
– Sampling (Desabie 1966; Cochran 1977);
– Expert systems (Dendral 1965; Mycin 1972);
– Quantitative Geography (Chisholm 1962; Haggett 1965; Berry 1967);
– Physical and chemical analysis (Archaeometry, name given in 1958);
– Quantitative environmental studies.

6. 1970. The revolution of multidimensional data analysis

The mathematical foundations of multidimensional data analysis have been well known since the beginning of the 20th century (Principal Component Analysis by Pearson 1901). But the computations for obtaining the eigenvalues during the process of diagonalising the matrix were too long to be used without computers. This was the reason why, around 1930, their development was limited to Psychometry (Spearmann, Thurstone, Guttman, Burt) by the definition of special questionnaires, simplifying the computations.

From 1960 to 1970, the first computerised algorithms appeared which were at the origin of a new revolution of Statistics. The multidimensional data analysis techniques included several different techniques:

– The Cluster Analysis techniques, figuring, mainly by a tree, the similarities between objects described by numerous variables and producing clusters of objects. 1963 is the year of the first publication of the famous book by R.R. Sokal and P.H.A. Sneath *Numerical Taxonomy*.
– The scaling techniques, reducing a multidimensional space of data to a one or two dimensional scale; the most famous of them is the *Non-metric Multidimensional Scaling* by J.B. Kruskal (from Bell labs), first published in 1964.
– The "Factor" Analysis techniques, a family of techniques based on the diagonalization of a matrix of correlation or association between individuals or variables, including Principal Component Analysis (Pearson 1901), Factor Analysis (Spearman 1904), Discriminant Analysis (Mahalanobis 1927; Fisher 1936), Correspondence Analysis (Benzécri 1973).

7. 1966-1976. The quantitative revolution in Archaeology

Around 1966, several papers marked the start-up of the quantitative revolution in Archaeology:

– Hodson, Sneath, Doran (1966): Cluster Analysis on Münsingen fibulae;
– Doran, Hodson (1966): Multidimensional scaling on upper Palaeolithic assemblages;
– Binford, Binford (1966): Factor Analysis on Mousterian assemblages;
– Archer, Archer 1963; Kuzara, Mead, Dixon 1966; Hole, Shaw 1967; Crayton, Johnson 1968; Elisseef 1968; Renfrew, Sterud 1969: Seriation algorithms;
– Renfrew, Cann, Dixon (1968): Characterization and exchange of obsidian around the Mediterranean sea (Archeometry).

In 1970, the Conference of Mamaia (Romania) *Mathematics in the Archaeological and Historical Sciences* was the place where famous statisticians met Archaeology: Rao, Kruskal, Kendall, Sibson, La Vega, Lerman, Wilkinson, Solomon, Doran, Ihm, Borillo, Gower, and where archaeologists also showed that they knew how to use statistics: Moberg, Spaulding, Cavalli-Sforza, Hodson, Orton, Hesse, Ammerman, Goldmann.

The Conference of Mamaia also showed the first use of data analysis in Archaeology and historical texts (Multidimensional scaling, Cluster Analysis).

The period from 1966 to 1976 is the time of the precursors, most of them were often trained in both Archaeology as well as Science and computers:

– USA: A.C. Spaulding, G.L. Cowgill, A.J. Ammermann, C.S Peebles, R. Whallon, E. Zubrow;
– UK: J.D. Wilcock, J. Doran, Cl. Orton, I. Graham, D.G. Kendall;
– Italy: A. Bietti;
– Germany: I. Scollar, P. Ihm, A. Zimmermann;
– Netherlands: A. Voorrips, H. Kamermans;
– Russia: P. Dolukhanov;
– France: F. Djindjian;
– Australia: I. Johnson;
– Denmark: T. Madsen;
– Belgium: A. Gob.

The next generation arrived in the period from 1976 to 1986, all of them being archaeologists: P. Moscati, A. Guidi, F. Giligny, S. Shennan, C. Gamble, J.A. Barceló, H. Hietala, K. Kintigh, K. Kvamme, J.M. O'Shea, S. Scholtz-Parker, S. Van der Leew, etc.

1966-1976 is the period of the greatest development of Quantitative Archaeology:

– Quantitative Archaeology (Doran, Hodson 1975);

– Environmental Archaeology (Butzer 1970);
– "Spatial" Archaeology (Hodder, Orton 1976; Clarke 1977);
– Simulation in Archaeology (Clarke 1972; Hodder 1978; Sabloff 1981);
– Image processing in Archaeology (Scollar 1975);
– Harris matrix (Harris 1975);
– Demography (Hassan 1973, 1981; Masset 1973);
– Site catchment analysis (Vita-Finzi, Higgs 1970; Higgs 1975; Zubrow 1975) ;
– Sampling in archaeological surveys and excavations (Mueller 1975; Cherry, Gamble, Shennan 1978);
– Mathematical models (Doran 1970, 1981).

8. Archaeology, Classical Archaeology and New Archaeology

The development of mathematics and computers in Archaeology has received varying degrees of acceptance, depending on the nature of the different theoretical approaches. Prehistoric Archaeology has preferred multidimensional data analysis for typometry, culture identification, spatial intrasite analysis, environmental studies. Classical Archaeology has given a significant impulse to data bank edition for epigraphy, to cultural resource management and to GIS implementing intersite spatial analysis. Processual Archaeology or New Archaeology, oriented towards Anthropology, functionalism and cultural ecology, had a preference for deductive models implementing statistical tests and mathematical modeling. Post-Processual Archaeology, of course, does not need any scientific method.

9. A case study: typometry

Artefact classification or typology is one of the basic methods of Archaeology. Until 1950, the classification was the result of a visual observation of artefacts, preferably spread out upon a large table.

The analogy with numerical taxonomy in Natural Sciences involves the formalization of a description of artefacts (attributes) which permits a classification on the basis of similarities between artefacts, quantified from the measurements in the description.

Numerous statistical approaches have been proposed; the main ones are cited below:

– *Attribute analysis* (Spauling 1953) is based on the use of χ^2 tests for measuring the association between attributes.
– *Matrix analysis* (Tugby 1958; Clarke 1962) is based on the reorganization of the rows and columns of a matrix of presence-absence or percentages to reveal a partition inside the matrix, demonstrating the evidence of several types.

– *Biometry* (Bohmers 1956; de Heinzelin 1960) is based on the use of Laplace-Gauss elementary statistics to reveal the existence of multi-modal peaks in histograms or separated point clouds in diagrams, to isolate types.
– *Numerical taxonomy* (Hodson, Sneath, Doran 1966) is based on the use of techniques of Cluster Analysis to identify archaeological types.
– *Typological Analysis* (Djindjian 1976) is an improvement of numerical taxonomy techniques. The Typological Analysis is based on a R + Q Correspondence Analysis and/or Principal Component Analysis associated with a Cluster Analysis. The *Multiple Typological Analysis* (Djindjian 1991) is based on several Typological Analyses applied on homogeneous intrinsic variables (morphology, technology, decoration, gripping, raw material, etc.) and a final one applied to the matrix of the clusters resulting in the previous analyses.
– *Morphology analysis* (pattern recognition) is based on multidimensional data analysis techniques applied to the digitalization of the profile of artefacts. Different codings of profile measures have been tested and proposed: Sliced method (Wilcock, Shennan 1975), Tangent-profile technique (Main 1986), Extended sliced method (Djindjian *et al.* 1985), B-spline curve (Hall, Laflin 1984), Fourier series (Gero, Mazzula 1984), Centroïd and cyclical curve (Tyldesley *et al.* 1985), Two-curves system (Hagstrum, Hildebrand 1990), etc.

10. A case study: seriation

Seriation is certainly the most original method in Archaeology for determining the chronological order of artefacts (from a description) and mainly between closed sets, particularly the burials in a cemetery (from an inventory of types). It is the reason why so many algorithms have been proposed to solve the problem of the seriation:

– Similarity matrix ordering (Brainerd, Robinson 1951; Bordaz 1970; Landau, de La Vega 1971);
– Graphs (Meighan 1959; Ford 1962);
– Matrix reorganization (Clarke 1962; Bertin 1973);
– Incidence matrix direct ordering (Kendall 1963; Regnier 1977);
– Computerised similarity matrix ordering (Asher 1963; Kuzara *et al.* 1966; Hole, Shaw 1967; Craytor, Johnson 1968);
– Rapid methods on similarity matrix (Dempsey, Baumhoff 1963; Elisseef 1968; Renfrew, Sterud 1969; Gelfand 1971);
– Multidimensional scaling (Kendall 1971);
– Travelling salesman problem (Wilkinson 1971);
– Reciprocal averaging method (Goldman 1971; Wilkinson 1974; Leroux 1980);
– Correspondence Analysis (Djindjian 1976);
– PCA (Marquardt 1978);

– Rapid method on incidence data matrix (Ester 1981);
– Toposeriation (Djindjian 1984);
– and others (Ihm 1981; Laxton, Restorick 1989; Baxter 1994; etc.).

Today, Correspondence Analysis is the most popular and easy to use technique of seriation, delivering a double parabola (the Guttmann effect), ordering chronologically both objects (burials) and types. The technique is very robust; it is able to reveal errors in recording or excavation and inaccuracies of typology, and permits separation of the time scales from other non-time parasite scales.

11. A case study: typology, assemblage, culture and "system"

When confronted with closed sets of artefacts, the archaeologist needs to compare them with others and to link the similarities between assemblages with time and space. It is the origin of the concept of culture which has many

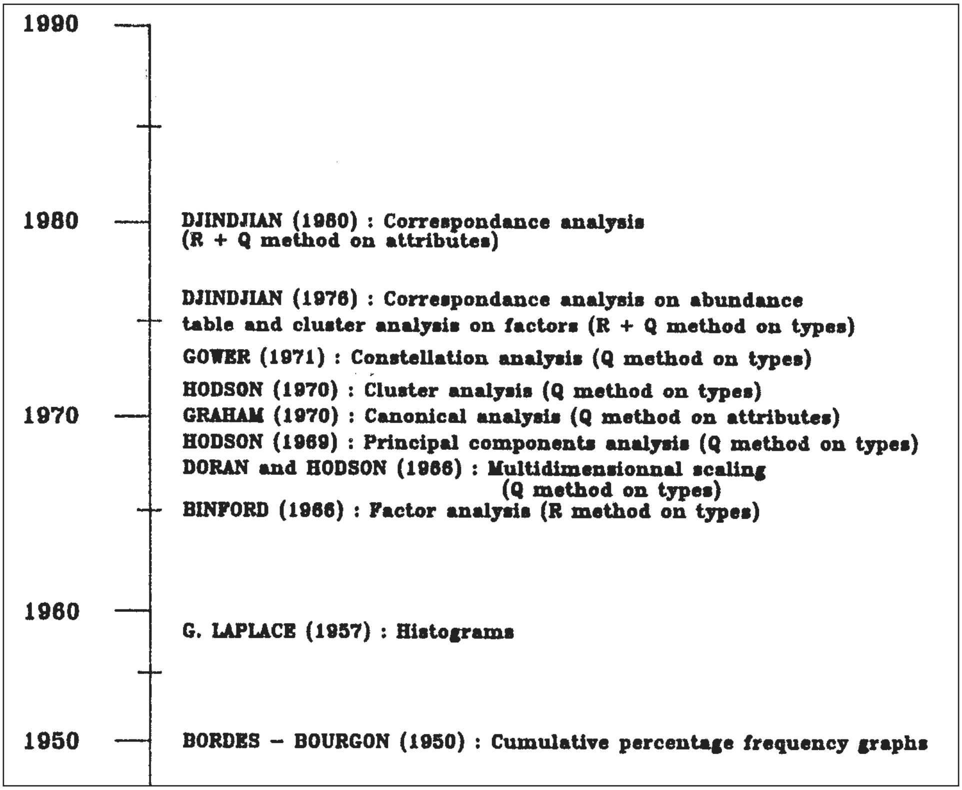

Fig. 1 – Proposed techniques for the typological analysis.

analogies in archaeological literature (techno-complexes, assemblages, facies, industries, cultures).

The archaeological methods proceed from artefacts to types (typology), and then from types to cultures, from a matrix of percentages of types in the archaeological layers, by searching partitions. The approach, generally limited to Prehistory and Protohistory records, starts from simple statistical techniques, inspired by Geology for the cumulative diagram of Bordes and Bourgon (1950) or based on histograms and χ^2 tests for Laplace (1957) and its synthetotype method.

The actual multidimensional scale of the problem has been well understood by Binford, Binford (1966) in their famous revision study of European Mousterian assemblages, refuted unfortunately by an incorrect use of their Factor Analysis. At the same time, the first use of a Multidimensional scaling algorithm by Doran, Hodson (1966) shows the potential of the multidimensional approach to solve the problem.

The technical difficulty was then to process both individuals (Q method) and variables (R method): several techniques were proposed around 1970, until the use of Correspondence Analysis applied either on contingency tables of types (Djindjian 1976) or Burt tables of attributes, thus avoiding the use of typologies (Djindjian 1980) (Fig. 1).

12. A case study: spatial analysis in Archaeology

The beginning of spatial analysis in Archaeology is associated with the influence of Quantitative Ecology (Pielou 1969): Nearest Neighbor Analysis, tests on grid counting. Whallon (1973) and Dacey (1973) were the first to apply these techniques to artefact distribution on occupation floors, for showing the evidence of concentrations. But rapidly, it was evident that the artefact distributions had a multidimensional component (lithics, ceramics, stones, bones, etc.) which could not be limited to a single one.

The tests of spatial associations were then proposed in the 1970s as a technical improvement: Hodder, Orton 1976; Clarke 1977; Hietala, Stevens 1977; Hodder, Okell 1978; Berry *et al*. 1980, etc.

But the only way was the use of Multidimensional spatial data analysis:

– Local density analysis by Johnson (1976);
– Spectral analysis by Graham (1980);
– (X, Y) clustering by Kintigh, Ammermann (1982);
– Unconstrained clustering by Whallon (1984);
– Spatial structure analysis with topographical constraints by Djindjian (1988);
– Spatial structure analysis of refitted artefacts by Djindjian (1997, 1999).

Such methods are always in the state of the art of spatial analysis. But the rapid development of GIS now involves the need to implement spatial analysis techniques in the GIS packages, as an easy to use function.

13. A case study: mathematical modeling in the 1970s

Various mathematical modeling techniques have been used in Archaeology, for example, algebraic and exponential equations, linear programming, stochastic process, gravity models, system dynamics, catastrophe theory, multi-agent system:

– Population model of hunter-gatherer groups (Wobst 1974);
– Fitting of logistic curves for demographic estimation of cities or regions (Ammerman *et al.* 1976): $Y = A/(1 + B\exp(-kT))$;
– Population estimation of hunter-gatherer groups from surface and structure of dwelling areas (Hassan 1975): $A = 0{,}7105\ P \exp 1{,}76$;
– Boundary models (Renfrew, Level 1979): $I = C \exp(a) – kd$ with $a = 0{,}5$, $k = 0{,}01$;
– Subsistence models (Jochim 1976; Keene 1979);
– Transition model from hunter-gatherer economy to farming and breeding economy (Reynolds, Ziegler 1979);
– Stochastic models for random walk process (Hodder, Orton 1976);
– Diffusion models of farming in Europe (Ammerman, Cavalli-Sforza 1973);
– Cultural change models by the catastrophe theory of R. Thom: the collapse of Maya civilization (Renfrew, Cooke 1979);
– Multi-agent systems and the Maya collapse (Doran 1981).

14. The 1980s: success

During the 1980s, the ability of multidimensional data analysis techniques to solve many archaeological methods was at the origin of its progressive success. Among the numerous classic or prototypal techniques of data analysis, Correspondence Analysis and Principal Component Analysis, associated with an appropriate Cluster Analysis, appeared to be robust and easy to use techniques, even to non-mathematician researchers.

Since then, Archaeology has played a major role among all the Human and Social Sciences, in showing how to integrate statistics into archaeological methods. Quantification, statistics, data analysis were then embedded in archaeological methods as they were embedded in computer packages:

– Survey (artefact surface collecting studies);
– Stratigraphy analysis (Harris matrix);

– Artefact analysis;
– Stylistic analysis;
– Taxonomy (Anthropology, Paleontology, Genetics);
– Identification of cultural systems;
– Seriation/Toposeriation;
– Intrasite spatial analysis (dwellings and funerary structures);
– Paleoenvironmental studies;
– Raw material procurement and craft manufacturing sources;
– Intersite spatial analysis and landscape studies;
– Any intrinsic and extrinsic structuring (general case).

15. The criticism against Quantitative Archaeology

At the end of the 1980s, Quantitative Archaeology and Statistics no longer seemed to be widely used. Many reasons have contributed to explain this situation:

– Quantitative Archaeology was passing from the field of research to the field of current use, corresponding to the publication of synthetic summary books (see bibliography).
– The available archaeological data were exhausted by the quantitative movement and it was necessary to come back to a new data acquisition phase.
– The ambitious objectives of the New Archaeology, often applied with a naïve approach and without enough mathematical and methodological know-how, were increasingly considered a paradigm rather than an epistemology of Archaeology.
– The development of microcomputers allowed the real development of Computing Archaeology and consequently the field of research shifted from mathematics and statistics to computing applications (data banks, GIS, Archaeological Information System, CRM, etc.) as occurred also in the other fields.

But general criticism concerning the quantitative movement in the Human and Social Sciences was also emerging, particularly concerning Structuralism, with the success in the USA of the French deconstructivism movement (Derrida, Foucault, etc.). The fashion of post-Processual Archaeology was then replacing Processual Archaeology.

Some of the main criticisms of the movement suggest that we should focus on the following:

– A measure is not knowledge (S.J. Gould, *The Mismeasure of Man*, 1981).
– A structure is not a system (deconstruction of the concept of archaeological culture).

– All the archaeological models fit well (poor quality of models, complexity of civilizations, data failure).
– The bias of the archaeological record does not allow any reliable quantitative or statistical process (Behavioral Archaeology).

16. 1990/2000: Standardization, embedding and theorization

Since 1990, the popularization of computers in Archaeology had involved not only a few enthusiastic archaeologists but, progressively, all of them. In the beginning, Computing Archaeology was mainly limited to Word, Excel, PowerPoint, Illustrator, Photoshop and a statistical package; but very quickly, the use of a DBMS, a huge interest for GIS and multimedia data banks, and the discovery of Virtual Reality were developed. Computing Archaeology has become not only the strategic weapon of the most dynamic researchers but also the professional tool for CRM (Culture Resource Management) and Rescue Archaeology. Internet may be considered as a revolution of productivity in Archaeology, for communication, on-line libraries, Google assisted retrieval systems, etc.

The decline of the scientific influence (Physics, Mathematics, etc.) in Social and Human Sciences becomes more and more evident, relayed by the Environmental Sciences (which have replaced the "old" Natural Sciences), boosted by the fear of the change of the earth climate and environment.

Statistical techniques are always present but they are increasingly embedded into computerized applications (Statistical packages, GIS, VR, etc.) and Archaeological methods (typometry, spatial analysis, raw material procurement, seriation, Harris matrix management, archaeological surveys, etc.): "Techniques are changing, methods are going on" (Djindjian 1991).

A further step has been the attempt to integrate Quantitative Archaeology in every Archaeological construct, with the objective of edifying a general theory of archaeological knowledge or Epistemology (Djindjian 2002).

It is also the end of a *factice* opposition between the methods of Mathematics (for example Djindjian) and the methods of Semiotics (for example Gardin):

– Quantitative	Acquisition	Qualitative
– Statistics	Object identification	Semiotics
– Structures	Structuring	Logic
– System	Modeling	Discourse

The two approaches may converge in a three step cognitive model as inspired by Peirce:

– Acquisition	Qualitative and quantitative acquisition
– Structuring	Data Analysis
– Reconstitution	Logic discourse and models

17. 2010?

Archaeology is changing!

The regional importance of cultural resource management, the rapid development of Rescue Archaeology as the prime budget and the first recruiter for young archaeologists, along with the specialization of archaeological research are all professionalizing Archaeology.

This context is promoting the elaboration of state of the art archaeological techniques and methods and the availability of computerized tools, which allows the emergence of standards (recording, reporting, thesaurus, etc.), good practices and productivity.

Quantitative Archaeology exists, embedded into application software, statistical packages and archaeological methods, but also through the conceptualization and the formalization of the archaeological projects.

Quantitative Archaeology has come back, because Archaeology is more and more a multidisciplinary Science, integrating Exact Sciences, Natural Sciences, Social and Human Sciences, Engineering, where the quantitative approaches are natural.

François Djindjian
Université de Paris 1 Panthéon-Sorbonne
CNRS – UMR 7041 ArScAn

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ABSTRACT

A major quantitative movement in all of the Social and Human Sciences known as Operational Research, started after the last world war with the application of mathematics developed for the optimization of war logistics. Since the 1960s, the fascinating progress of computer technology in the field of scientific research has amplified the movement which saw the first applications to Archaeology around 1966. At the time, the success of a Quantitative Archaeology was associated with the revolution in multidimensional data analysis, which occurred with computerisation and improvements in the algorithms, mainly Multidimensional scaling, Factor Analysis, Principal Component Analysis, Correspondence Analysis and various Cluster Analyses. The Conference of Mamaia (Romania) in 1970, which may be considered as the first and most spectacular scientific event of this period of foundation, found expression in the book *Mathematics and Computers in Archaeology* by Doran and Hodson (1975). From 1975 to 1985, the quantitative movement experienced its finest period with the transition from the research field to the application field, both for algorithms and software, and the diffusion of Correspondence Analysis, Principal Component Analysis associated with Cluster Analysis and their use by archaeologists. Numerous papers and books were published during that period. After 1985, the quantitative movement fell into disfavour, probably due to the "deconstruction" paradigm and the passing fashion of expert systems. Nevertheless, it is also possible to state that Quantitative Archaeology had now definitively entered into the standard methods of Archaeology.