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ARCHEOSEMA
Artificial Adaptive Systems for the Analysis of Complex Phenomena

Collected Papers in Honour of David Leonard Clarke

edited by
Marco Ramazzotti

ARCHEOLOGIA E CALCOLATORI
Supplemento 6, 2014

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PRESENTATION

Anyone who has selected a career in a subject matter that assumes a strong research component likely acknowledges an ethical responsibility to advance the knowledge of that discipline to some higher level. This is the essence of research: to add to the knowledge base of humanity. Some research is quite esoteric and may be considered little more than a creative footnote while another might be worthy of Nobel recognition. Many, unfortunately, live their careers in the area of the former though we believe our research is worthy of greater acknowledgment.

When I was originally approached to write an introduction to this book I assume it would be much of the above former case but, to my amazement and pleasure, the topics addressed in this book immediately caught my attention not only because of the scientific merit, but also because the areas of application were novel and exciting. As a Systems Scientist my background is, by definition, multi-dimensional and multi-domain. Systems Scientists seek to identify the underlying structure of complexities and apply those insights to the investigations of other complex problems in other possibly entirely different disciplines. You will be equally impressed, I am convinced, as you peruse this book as to its innovative and contributive nature to the areas of general systems, philosophy, archaeology, geography, anthropology, art history, linguistics and even literature!

The one common thread weaving this fabric of excitement together with science is the domain of Artificial Adaptive Systems (AAS). For the reader who is already adept with the concepts of AAS there should be little difficulty in understanding the material but for everyone else, I will offer here a brief and conceptual presentation of AAS with only enough detail so one can delve into the chapters as long as one assumes the mathematics to be accurate. I shall begin with a discussion of Artificial Intelligence.

The raw material of science, it can be argued, is the *datum*. A single *datum* can be observed, measured, sensed, implied, or by other means acquire an understanding of an event by way of a number. A number may represent the degree of brightness, the quantity of growth, the number of items, a feeling or attitude, etc. but it is the number applied to that single event that is the essence of scientific research. We measure, quantify, qualify, and so on to better understand the event in question. But a single *datum* is typically not useful. Statistics tells us that we need much more data, at least 32 data points, before we can use the language of science: mathematics. So we collect as much data as reasonably possible. This task might be formidable given some scientific obscurity, but the world now creates billions of transactions each day amounting to about a doubling of the world's data every two years or so. This has resulted in the development of a concept and its consequent tools for the analysis of big data and is a source of much research but the subjects here are the result of limited amounts of data, such as what one might collect in excavating some archaeological site or from some medical measurements concerning some disease whose scope is extremely limited.

Here it is important to extract as much knowledge as possible from the limited data, and it is not altogether unexpected to discover that traditional statistics does not have the strength to extract much information. This is not to be an indictment of statistics but rather, the acceptance that the field of mathematics was created at a time that preceded computer technology so there are understandable and logical limitations to what can be extracted from a given quantity of data using these traditional pencil and paper tools. There are rules, axioms, theorems, etc. that one is required to follow if one wishes to properly use statistics. But even if all the rules are properly followed it can be argued that there remains information contained in the data that is beyond the purview of statistics to extract. It was not until the mid-1940's that the notion of using a computational model based on biological concepts came into existence with Turing's B-type machine. Alan Turing considered an infant's cerebral cortex to being akin to an unorganized machine which would, over time, become organized. He sought to emulate this concept and suggested an A-type machine, essentially composed of randomly connected networks capable of some very simple activities, and a B-type machine that expanded the A-type machine such that it contained a kind of connection modifier.

This was to be the origin of Artificial Intelligence, eventually a system of input nodes each representing a variable, output nodes representing the recognition of a pattern or outcome, and a set of hidden nodes that linked the input nodes with the output nodes. These hidden nodes are assigned initial weights that together capture the knowledge contained in the input variables. This is accomplished by the iterative modification of these weights until some measure of error is reduced to an acceptable level. The final values of the weights at the conclusion of the algorithms are deemed to contain the knowledge of the system, and it might take a prepared mind to creatively understanding the meaning.

Neural Networks (NN) are not without their risks. Each NN must be trained to extract the meaningful data that becomes these weights and if it is done correctly we can say that we have a model for understanding the structure of the system under investigation. This is accomplished by training the system. The NN must learn all that is necessary to clearly establish the patterns in the data, but no more than enough. If too much leaning occurs then the data that defines the structure of the system also contains "noise" data that is not a part of the system structure. When this happens the NN may lead to wild predictions far beyond what is actually happening in the data. On the other hand the NN may not learn enough to be able to predict the optimal system structure. There is a point at which the ideal learning has taken place and there are algorithms designed specifically to know when enough is enough. Therefore, a method must be determined by which it is possible to know when the amount of training is optimal, and that requires some way to make the NN adapt itself. These algorithms are adaptive and the result is an Adaptive Neural Network (ANN). The mathematics can be a challenge to understand but, if one is willing to commit the time and energy to the task, it can be mastered.

There is substantial literature available in the field of Neural Networks and Adaptive Neural Networks as the field of Artificial Intelligence has been experiencing a resurgence since it fell out of favor in the 1970's. The promise of AI was never realized and there were many other newer opportunities available to the scientific community into which they could direct their energies. That promise of "intelligence", however, is now being realized but in ways that are not necessarily making the evening news. There have been many meaningful advancements made in the area of medical diagnostics, but these methods are not understood or worse, unknown, by too many of the medical community and unfortunately they, as a group, seem happy maintaining their comfortable *status quo*. Similarly, advances have been made in law enforcement but there is seemingly little interest expressed.

This book seeks to make a difference. It will appeal to the scientist, of course, but also the practitioner seeking to find a unique way to solve a complicated problem, the graduate student seeking direction in the pursuit of a research topic, and definitely there is much for the arm chair academic. The corporate executive who possesses an open and prepared mind will also find much here that can be applied to garner competitive advantage, for the scientific applications describe unique visions and those who are strategic visionaries will also be quick to understand the potential for success.

I recall something of a *mantra*: all the simple problems have already been solved! There was a time when being adept at regression provided insight into the future. In this current age regression and its various modifications is as commonplace as the mean. The science of neural technologies has permitted us to learn more of the future by listening more closely to the past. There exists more information in historical data than we have extracted using the methods of the past. In another few years I will probably be making this assertion again, but with another yet-to-be-discovered set of analytical methods. But at this current time, what is presented here is the cutting edge of neural technologies and ripe for use in virtually every knowledge domain.

Like most researchers, I consider myself to possess a certain required level of scientific curiosity that was piqued during my reading of these manuscript-chapters. There is much originality in the approach taken to historical, archeological and anthropological research using Adaptive Neural Network technologies. This is an exciting time for those researchers in this remarkable field, and it is equally exciting for those who will take these advances and move them to the next level. I shall enjoy my time reading about them in the forthcoming years.

William J. Tastle
Ithaca College, New York

Archeologia e Calcolatori
Supplemento 6, 2014, 11-14

PREFACE

ARCHEOSEMA (AS), a meta-disciplinary project of theoretical, analytical and experimental archaeology, has been recently awarded by La Sapienza University of Rome. The project title is an acronym which sums up its two main theoretical foundations: the openness of modern archaeology (ARCHEO) to the analysis of physical, historical, linguistic signs (SEMA) underlying natural and cultural systems reconstructed and simulated through Artificial Sciences (Fig. 1).

The project is therefore connected to the construction of models conceived as both epistemological and methodological tools: indeed, on the epistemological level, ARCHEOSEMA is an interdisciplinary research program founded on the constructive dialogue between theoretical and experimental Archaeology with Physics, Mathematics, Statistics, Geography and Linguistics (Ramazzotti 2010); on the methodological level, it aims to solve problems of classification, organisation and structure of alphanumeric data; to implement dynamic simulation of the variables that constitute natural organic systems and/or cultural systems; to identify new rules for spatial organisation and, in addition, to explore the physical, aesthetical, linguistic and cognitive phenomena underlying isomorphism, self-organisation, entropy, learning and translation (Ramazzotti 2012, 2013a, 2013b, 2013c, 2013d).

The design of these models is based on a computer-programmed architecture that integrates relational capabilities of Database Management Systems (DBMS), Geographic Information Systems (GIS) and Artificial Adaptive Systems (AAS). Analysis, applications and experiments are currently being conducted by a team of young archaeologists, physics, geographers and linguists at the LAA&AAS: Laboratory of Analytical Archaeology and Artificial Adaptive Systems (Luca Deravignone, Alessandro Di Ludovico, Benedetta Panciroli, Irene Viaggiu, Claudia Di Fede, Juliette Wayenberg, Massimiliano Capriotti). The LAA&AAS has been inaugurated in the Faculty of Letters and Philosophy of La Sapienza University of Rome thanks to the joint institutional efforts of the Department of Sciences of Antiquity, Department of European, American and Intercultural Studies, Physic Department and Semeion Reserch Center. The disciplines involved in the research programme are those of Artificial Intelligence and Mathematical Biology (prof. Paolo Massimo Buscema and dr. Massimiliano Capriotti), Physics of Complex Systems (prof. Vittorio Loreto and prof. Alessandro Londei), Computational Linguistics and Dynamic Philology (prof. Paolo Canettieri and prof. Simone Celani), Economical Geography and Spatial Analysis (prof. Armando Montanari and prof. Barbara Staniscia), Physical Anthropology and Human Population Genetics

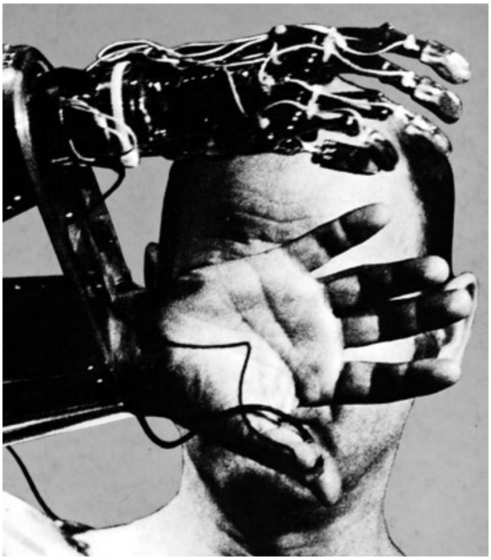

Fig. 1 – Photo by G. Azali (de Kerchove 1996).

(prof. Alfredo Coppa, prof. Franz Manni and prof. Francesca Candilio) and Mathematical and Multivariate Statistics (prof. Giorgio Alleva, prof. Maria Felice Arezzo and prof. Filippo Belloc). Finally, it is worth mentioning that this experimental integration between Analytical Archaeology, Geographic Information Systems and Artificial Adaptive Systems has become a core of two European projects of the 7th Framework Programme (FP7) recently acquired by La Sapienza University of Rome: the contribution of the LAA&AAS to the achievement of the objectives of these two international research projects was recently published (Ramazzotti 2013b, 2013c).

This Supplement to «Archeologia e Calcolatori» is a special issue dedicated to the memory of the English archaeologist David Leonard Clarke (3 November 1937-27 June 1976), and is a further attempt to collect some applicative studies of complex natural and cultural phenomena following the Artificial Intelligence computational models through the lens of *Analytical Archaeology* (Clarke 1968). In fact, these complex phenomena are essentially understood to be the product of cognitive behaviour, in other words systems and ideal-types which represent it and can be analysed on a formal logical level. This preface leads the historiographical tribute to Clarke's reasons of his "collected papers" (Clarke 1979) and a syntactic classification of the main logical inferences to trace archaeological reasoning back to the simulation of cognitive complexity. Artificial Adaptive Systems, as new mathematical tools expressing the emulative properties of such cognitive complexity, motivated the "connectionist" reaction to "behaviourism" and therefore could effectively impact on the epistemic nature of contemporary archaeological thought, since systems complexities are developed by our brains and analysed by simulating variables nets with non-linear and dynamic computational models of Artificial Intelligence, Computer Science and Computer Semiotics.

During the 1970s Cybernetics, introduced by D.L. Clarke in the archaeological research essentially as Systems Theory, contributed to consolidate, in the UK, in the USA and in Europe, the idea that the archaeological, linguistic and anthropological cultures work as natural organisms and that their organic-biological function could be simulated as a mechanical operation of interconnected parts, driven by an input. These parts would be able to report the whole process that caused the balance alteration, and such alteration would not be that different from those observable in the so-called cultural systems.

However, this mechanisation of cultural complexity has turned the research away from other possible analogies that could contribute to resolve highly complex problems, and has especially radicalised a single meaning of complexity, as a factual dimension outside the man, a cognitive nature independent of human existence itself. But since the late 1980s, a large number of studies have been conducted in an attempt to understand the complexity of archaeological, linguistic and anthropological contexts not as being external to the human being, not as passive objects of his research, but rather as a dynamic expression of his own perceptual constructs. In this sense, this complexity has been almost subtracted from the uncontested historiographical domain of being interpreted as an external object investigable through mechanical and linear systems, and has become the subject of specific researches that are traced back to the cognitive capacity of man to create it.

There is thus the possibility to organise, by analogy between cultural and cognitive complexity, a new apparatus of theoretical knowledge, methods and applications that connects analytical research and Artificial Intelligence (Ramazzotti 2010, 171-198). The researcher who simulates the dynamic behaviour of a complex system through these models of Artificial Intelligence will therefore explore the configuration data (which have been learned) as a hypersurface of trained connections. Therefore, instead of describing the purely systemic complexity of a given context, the researcher will tend to act on that context translated in alphanumeric matrices and trained by means of Artificial Adaptive Systems in order to test every possible combination of the trained hypersurface. An analytical and computational study of archaeological complex systems that would benefit from Artificial Intelligence is, ultimately, a study that evaluates the "meaning" of data relationships as an essentially human learning, physically connected to the computational capacity of the neural networks.

This type of study would therefore repeat a still strong Analytical Archaeology position but would also update this position to the progresses made by Artificial Intelligence in surpassing the limits imposed by Systems Theory, on the basis of the progresses achieved every day by Cognitive Sciences in recognition, in play, in simulation and classification of some of the principles governing memory, orientation and language.

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ANALYTICAL ARCHAEOLOGY AND ARTIFICIAL ADAPTIVE SYSTEMS

1. Back to the future. A tribute to the memory of D.L. Clarke (1937-1976)

In the late 1960s, David Leonard Clarke published *Analytical Archaeology*, a brilliant and unique synthesis that intended «to draw attention to specific areas and archaeological periods towards the General Theory that is the basis of modern archaeology» (Clarke 1968). At the same time, the Author introduced the first chapter of his main theoretical essay with a quote from Lewis Carroll's novel *Alice's Adventures in Wonderland*: «here ... you must run as quickly as you can, if you want to stay in the same place». Since then a quick run has been carried out but, even though the archaeologies have been approaching new methods, tools and techniques, the heart of Clarke's reflection on drafting a new General Theory of the archaeological thought has slowly dissolved. It has been assimilated in the story-boards of studies and registered as an unresolved utopia, nonetheless interposed between the current scientific archaeology and the earlier or pre-paradigmatic archaeologies – as they have been named.

This Supplement to «Archeologia e Calcolatori» is the empirical consequence of theoretical approaches I advanced in *Archeologia e Semiotica*, since it derives from the desire to renew the empirical research on complex phenomena applying the new methods of Artificial Intelligence through the lens of Analytical Archaeology and collecting different and specific applicative case-studies (Ramazzotti 2010, 128-170). We do not know if this kind of intervention on the record's semiosphere, on the past interpreted and on the past to be interpreted, will contribute to the «loss of innocence» hoped for the future growth of the discipline by Clarke (1973), but we are convinced that the new research methods opened by Neurosciences and Artificial Intelligence will add an inner critical view-point on our present and future works.

Analytical Archaeology is perhaps the most representative, unfinished, document of the humanistic interest for data semantics, a grammar for the analytical reasoning and a syntax for its cognitive structures. A world-view is underlying it, but has not been performed or emphasised yet; the archaeological theory is strictly linked to the philosophy of science and becomes experiment. The first systemic natural and cultural mechanisms are now described without formulas, with the distance from the tool the humanist should maintain, without ignoring their logics. It would be pointless to read *Analytical Archaeology* without having first tried to imagine what contexts

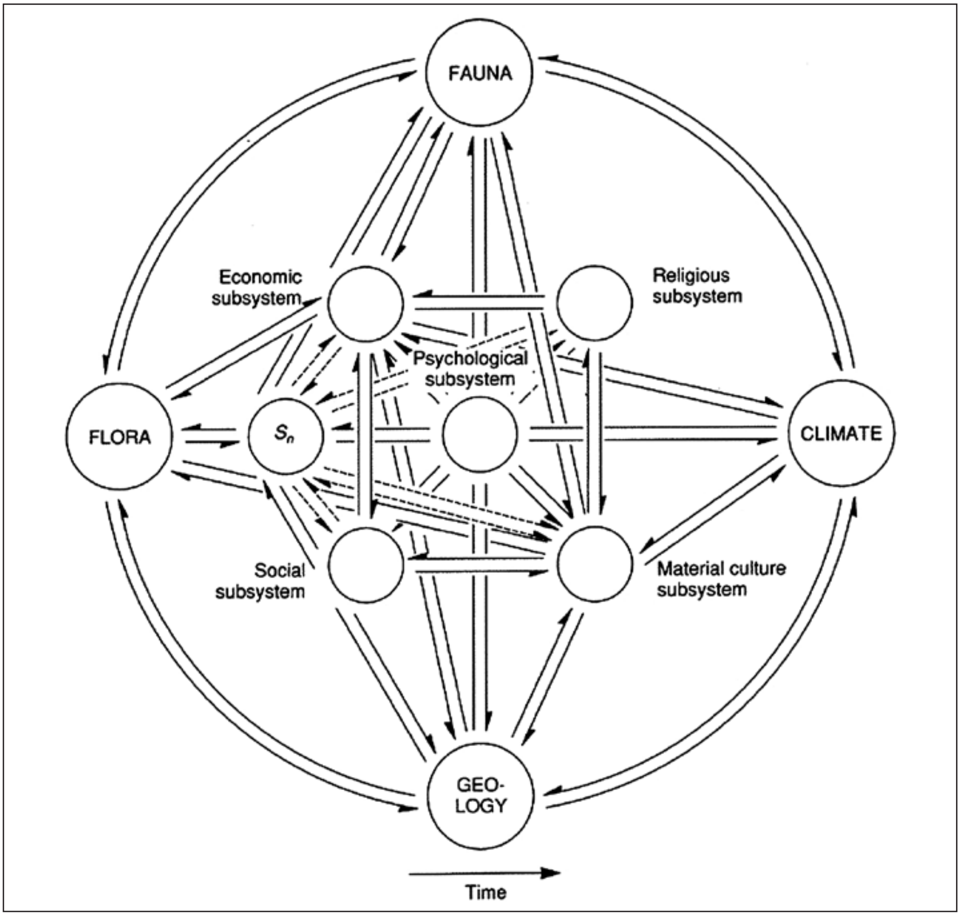


Fig. 1 – Culture as a system with subsystems. A static and schematic model of dynamic equilibrium between the subsystem network of a single socio-cultural system and its total environment system. The internal setting of subsystems within the general system constitutes cultural morphology, as opposed to the external setting of the system in its environment, comprising cultural ecology (Clarke 1968).

were behind the analysis of real world's segments through the processes, systems and models. Yet Clarke appears to have nearly revived this approach to the so-called complex phenomena, by attempting to qualify not only the form and matter of the record, but also the interconnected networks of "entities" able to simulate dynamic relations (Fig. 1).

In the UK, after Gordon Vere Childe (1892-1957), John Grahame Clark (1907-1995) argued, in an original way, its clarification in the concept of culture. Clark's major works are influenced by the theoretical commitment of the Australian archaeologist, although the Cambridge scholar sought not so much to act on the semantic level of the object, but rather on how Palaeoeconomy, with the contribution of natural sciences, would be able to recognise the subsistence techniques (Coles 2010). And it is this attention to the method's superstructure to be still intact in the *Analytical Archaeology*, because although Clarke was certainly addressed to collect the best techniques (statistical and mathematical) to analyse and classify the archaeological records in their spatio-temporal contexts, his work would probably never have been conceived if it were not firmly concentrated on the discipline's redefinition founded on the analysis of the data multi-factorial meanings (Ramazzotti 2010, 171-198).

In other words, what these considerations denote is the fact that this British Archaeology and its ideal-types, structures and models, by studying the archaeological data with the help of empirical languages, supported a deep knowledge of the record's semiosphere and of the relationship between structure and superstructure, but was also extremely involved in the evolution of the scientific-materialist thought, interpreted as a form of cognitive process, and adapted it to the questions posed by the philosophy of science. In this perspective the scientific-materialist thought seems to have answered these questions, about a decade in advance, with the criticism of the post-processualists, who were boasting of the primate of historicism in historiography, and of their idealistic methods. In fact, in the late 1970s, British archaeologists were also among the first to move from that epicentre to collaborate directly with French economic anthropology: so, while the early works of Ian Hodder insist on the non-linear relationship between structure and superstructure (Hodder 1982), those of Daniel Miller and Christopher Tilley, shortly after, are already focused on the concrete possibilities offered by the archaeological techniques to the reconstruction of the ideology of power through the study of material culture (Miller, Tilley 1984).

In addition, in conjunction with the external use of the materialist lexicon, other researches, such as Trigger's, focus on the Marxian evaluation of the impact of the social conditioning on the historical-cultural criticism (Trigger 1981b), and yet others tend to introduce the debate about objectivity and subjectivity in the historical analysis (Rowland 1984). In 1968 Clarke proudly defends the centrality of his own research position by repeating that: «archaeology is the archaeology, is the archaeology, is the archaeology», in the sense that – we would add – it transformed the grammars of the archaeological contexts in coding languages, summarised those languages in theoretical models, approached the model-system relationship in terms of logic (proposing a logic-based approach to the relationship between model and system), and inaugurated the thriving debate on the applicative use of inferential statistics. This archaeology does not minimise the complexity of such abstractions, but goes much more in depth in the conquest of the semantic significance – if this term can be adopted – of the document.

2. From System Theory to cognitive complexity

The attempt to increase the expressive potential of the record induced Clarke to treat it as a sign (*sema*), interpreted not as a unit in a system explaining only its historical and anthropological meanings, but rather as a node connected to a network of open cultural, technological and biological variables in continuous combination with each other. By comparing the supposed operational rules of organic systems and cultural systems centred on artefacts, *Analytical Archaeology* operates the brilliant conversion of the cultural complexity into a physical-biological complexity. This is the indelible legacy left by Clarke's early and greatest work, which also led to the desire for a radical transformation of the cognitive morphology of the discipline (Fig. 2).

However, by talking of this transformation of the discipline we should not simply mean an attempt to summarise the cultural complexity, since that would represent, and Clarke was aware of this, a somehow fruitless attempt. But we should rather highlight the fact that the models he created and classified always aimed at specifying every assessable segment of cultures, conventionally understood as Complex Systems. This measurability of relationships, mapped out with the pioneering aid of Cybernetics, was *de facto* the first and still unequalled attempt to offer an explanation for the operation regulating the interaction between the parts of a system, an explanation that would be able to make decisive use of the contribution of both mathematics and the nascent new mathematics.

Cybernetics, which Clarke explored as the direct expression of Systems Theory, offered him an appropriate language to consolidate the analogy between cultures and organism and, in the early 1960s, Cybernetics was essentially intended as the mechanical operation of interconnected parts; driven by an input, these interconnected parts would be able to report the whole procedure which caused the alteration of the *equilibria*, and the results observed would not be very dissimilar from those observable in the so-called cultural systems.

The contemporary computational models that are still using analogue operators are divided into three types (French 2002):

1) Symbolic models: they refer to the paradigms of Artificial Intelligence and allow analogue codification of information to be examined by constructing more extended generic classes;
2) Connectionist models: they process relationships between differentiated objects and classes of objects, allowing the degrees of similarity to be measured;

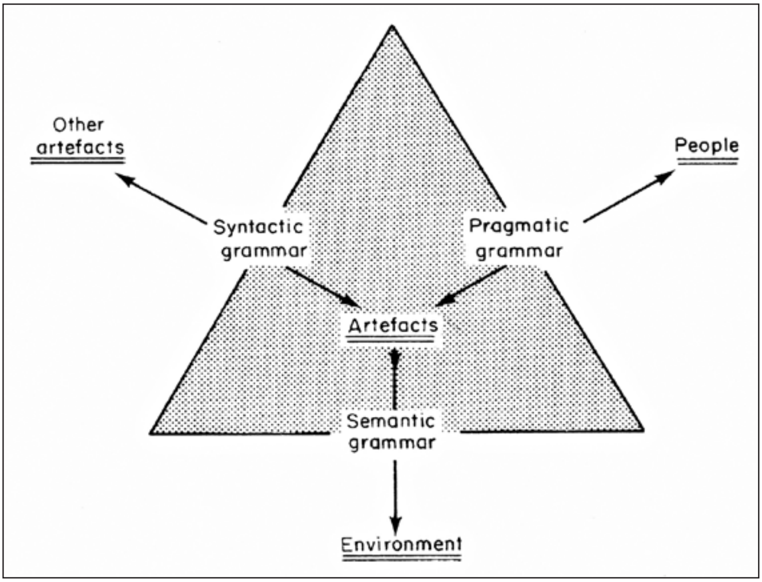


Fig. 2 – The three archaeological interactions grammars (Clarke 1979).

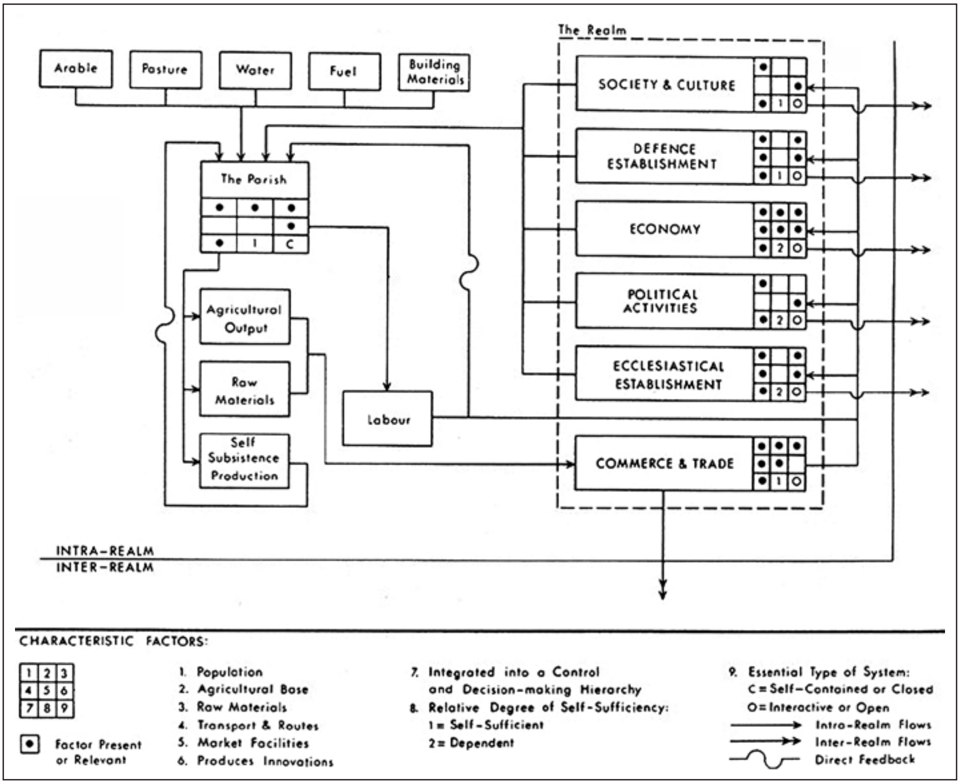


Fig. 3 – Code that formalizes the systemic operation of a Danish parish defining logical operating characteristics (Clarke 1979).

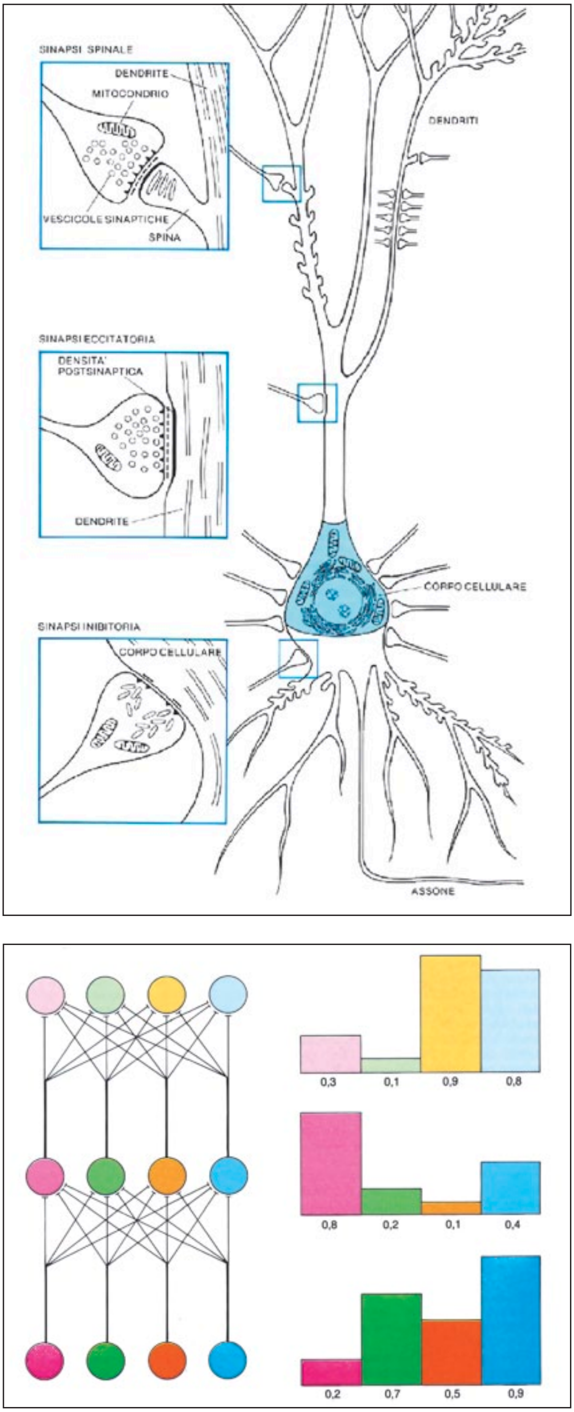
3) Hybrid models: they constitute architectures which integrate the functions of the first and second groups.

This mechanisation of the cultural complexity, as well as its transfer to the level of the mathematical discussion of the action performed by one or more factors on its entropy (Edelman 2004, 131), has then inspired almost half a century of experimental archaeology and has become a standard practice in the anthropological research, above all in the USA. Over time, nevertheless, the measurement of the difference between Cultural Systems and Mechanical Systems has been turned into the study of the cultural complexity through its reduction to groups of calculable parameters, and Clarke's central idea has been, in a certain sense, set aside (Fig. 3).

The insertion of the cultural variability in the more refined and contemporary Systems Theories and Expert Systems prevented from the search for other possible analogies that could have been involved to solve highly complex problems and, above all, radicalised a unique meaning of complexity itself, in other words its expression as external to man and independent of the human cognitive nature, as a product existing in and of itself and being the specific topic of the research (for these issues opened up by Computational Archaeology, see: Clarke 1962, 1968, 1972; Binford 1965; Gardin 1970; Level, Renfrew 1979; Bintliff 1997; Barceló 2008; Ramazzotti 2010, 171-198, 2012, 2013a, 2013b).

But at the end of the 1980s, numerous studies resurfaced in the attempt to understand complexity no longer as external to man and subject of our predominantly applicative research, but rather as a living expression of our constructive, mnemonic, perceptive capacities. In this sense, complexity was almost completely removed from the undisputed supremacy of external interpretation, able to be analysed through mechanical and linear systems, and became the subject of specific researches which aimed at recognising the man's cognitive development (that created it). The analogy between cultural complexity and the complexity of intelligence then gave birth to a new system of theoretical knowledge, methods and applications correlating archaeological research and Artificial Intelligence.

Those theories, methods and applications are already in use and identify a whole new world of archaeology, which is not a paradigm of it, as Cognitive Archaeology aims to be, but a (contemporary) way to undertake the same historical reconstruction (for the issues opened up by Cognitive Archaeology, see: Zubrow 1994; Doran 1996b; Gardin 1996b; Djindjian 2003; Zubrow 2003; Malafouris, Renfrew 2010; Ramazzotti 2010, 128-198, 2013a, 2013b). Indeed, while we certainly cannot debate the possibility to recreate intelligence artificially, it is equally evident that many models emulate and quite clearly come close to some segments of the cognitive process – memorisation, classification, orientation, reflection and perception (Fig. 4).



a

b

Fig. 4 – a) The synapses, which are based on a neuron in the brain, are excitatory or inhibitory depending on the neurotransmitter released (Storti Gajani 1982); b) Example of a three-layer ANNs in which input neurons (bottom left) elaborate a configuration of activations (bottom right) and transmit to one hidden layer (centre) on the basis of synaptic connections weighed. Hidden layer elements sum the inputs and produce a new configuration of activations (above) which is determined by the intensity of the connections between neurons (Churchland, Churchland 1982).

Transferred to the level of the necessary logical-mathematical identity, the "entities" of the cognitive complexity can be compared with nodes (neurons), and the relations (synapses) which regulate their inner dynamic functions (networks) are called connections (on the operation of Artificial Neural Networks, see: Minsky 1954; Minsky, Papert 1968; Amari, Arbib 1977; Grossberg 1982, 1988; Hopfield 1982; Anderson, Rosenfield 1988; Zeidenberg 1990; Kosko 1992; McCulloch, Pitts 1993; Arbib 1995; Kohonen 1995; Bishop 1995; Kasabov 1999; Szczpaniak 1999; Smolensky, Legendre 2006; Ehsani 2007; Nunes de Castro 2007; Buscema, Tastle 2013; Tastle 2013).

The terms imply another important "conversion", that of the biological-cognitive complexity of the world of intelligence into physical-cognitive complexity of the system of intelligence which, in this manner, enhances the processes of simulation and analysis by advanced computational models. Today, there is unceasing talk of Computer Semiotics as a discipline aiming at establishing the function of the logical operators of programming on the basis of structured and complex semantic units, but the semiotic analyses centred on redefining the analytical object are also one of the main trends in Computer Science and, in particular, in the sector interested in constructing nodes or cells composing many of the artificial models of the Artificial Adaptive Systems' class (Beckerman 1997; Miller, Page 2007; Ramazzotti 2012, 2013b), whether they are synthetic representations of the observed reality which must undergo interrogation processes (Expert Systems, Cellular Automata, Logical Networks) or the most advanced analytical tools for learning and modelling complex configurations (Artificial Neural Networks, Contractive Mapping, Genetic Algorithms).

Given these basic coordinates, it seems clear that simulating the behaviour (dynamic and complex) of the high variability of the cultural factors in networks thus conceived equals tracking down, selecting and recreating (separately) a wide variety of functions associating variables, a wide variety of inferences controlling their semantic structure and an equally wide variety of causes producing their transformation (Zubrow 2003; Bintliff 2005; Barceló 2008, 154-184; Renfrew 2008; Malafouris, Renfrew 2010).

This perception of functions, inferences and causes that generate and multiply the complex phenomena requires an archaeology interested in interpreting the past by debating the history itself of its different perceptions and, at the same time, attentive to the recognition of the cultures complexity by contrasting the classical and dualistic models, in order to display all its extraordinary variability and richness. In this specific sense, the application of Artificial Intelligence models to the archaeological problems has value: it recreates a possible world of other associations of meaning from the body of lacking sources and dispersed information, exhibits the nuances and complex interrelations and, furthermore, helps the researcher to codify other, unforeseen (or hidden) interrelations. In a certain sense, this is in itself a sort of metaphor illustrating the fact that the intelligence's complexity is related to culture's complexity.

3. Encoding cultural systems through the construction of a *lingua characterica*

The logical-formal description of the cognitive complexity is the subject of the latest epistemological debate in History, Archaeology and Anthropology, since cognitive complexity must be intended as one of the most important themes for the construction of a research method. Since the mid-1980s descriptions have been advanced using data coding techniques, intended as scientific tools for the construction of a *lingua characterica* capable of generating valid propositions and of overcoming the structural constraints of these artificial languages. It is almost natural that this intent is now bringing to the renewal of interest among those, especially historians and archaeologists, who founded their researches on deductive reasoning according to the Aristotelian and Kantian tradition, since the *lingua characterica* translation of the possible historical, archaeological and anthropological contexts – as Clarke already perceived – represents an attempt to recover the information exchange of every lost item (Clarke 1968, 485-486).

3.1 *The deductive inference*

Analyses and methods using the deductive inference tend «to *predict* the Result of a (true) Law through a Case» and to return that result (model) which represents a projection of the historical meaning ascribable to the data, in other words its prediction. Nevertheless, it has been noted that no automated reasoning programme can be universal, in the sense that it is necessary to decide for any set of inference rules and axioms, whether or not a given symbolic expression is a theorem of the theory in question and, if it is, supplying an effective deduction procedure (Pessa 1992, 83). Within the Humanities, the observations of the mathematical, statistical, economic and geographical relationships processed for a given body of data are represented with tables, matrices, histograms and dendrograms which perform the dual purpose of spatialising and structuring the values, the percentages, the trends and the intersections between a limited number of variables. These graphs are therefore models which summarise the repeated observation across multiple cases, as a result expressed through frequencies whose different variation and intensity always constitutes a degree of (cultural) intentionality. The cultural intentionality in a given production of artefacts indeed presupposes the concept of "type" as a principle, a finite planning entity, expressed by the intentional

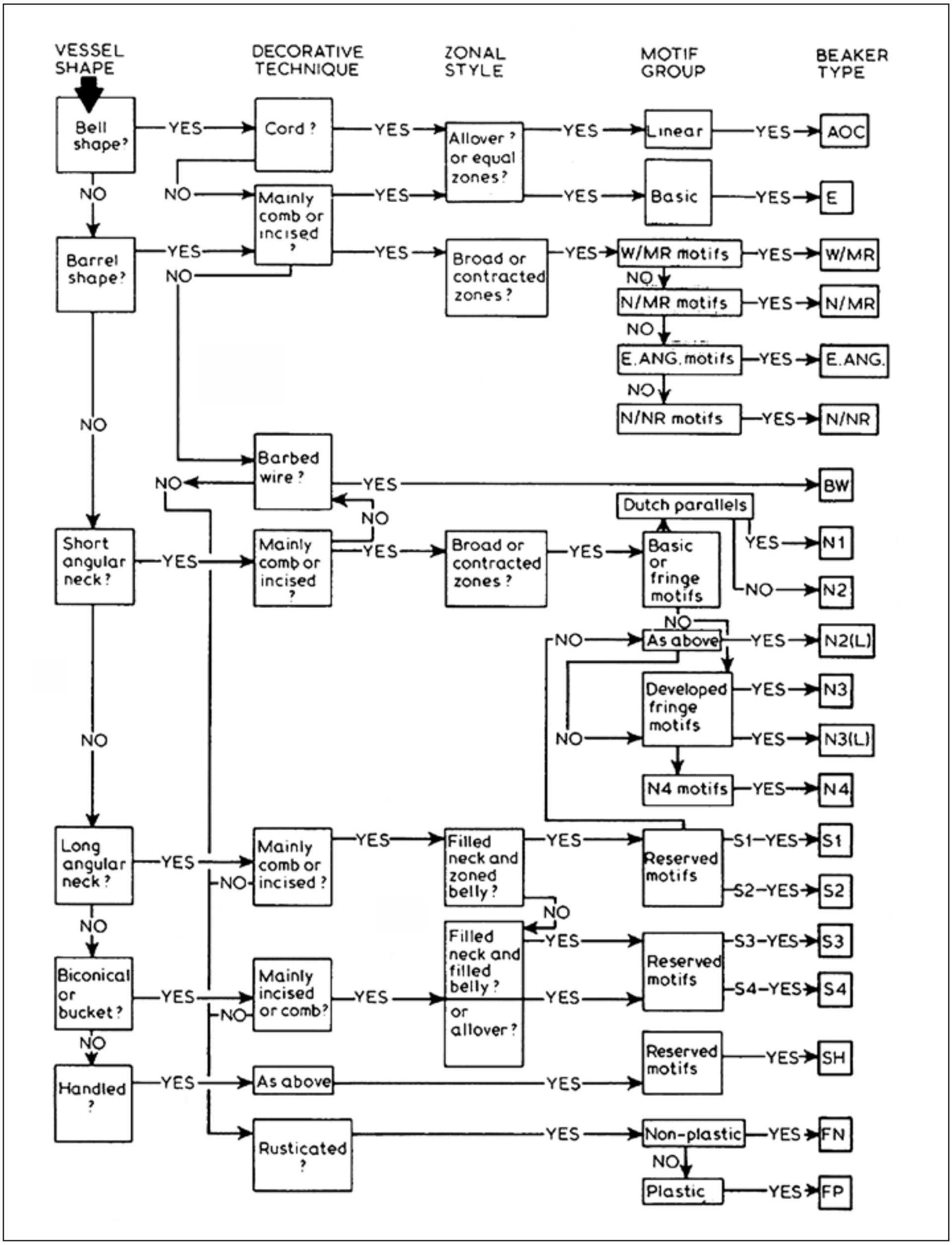


Fig. 5 – Combinatorial model developed by Clarke to classify and interpret the pottery beaker; the algorithm draws two different combinatorial routes that produce a high diversification of types (Clarke 1970).

correlation of different attributes. Each hidden organisation of the attributes defines the characteristics of a type, multiple types the characteristics of a class, and a class the "intentional" product of a culture (Fig. 5).

The analyses used first by *Analytical Archaeology*, and today by many other disciplines of the so-called Social Sciences, to classify attributes, types and classes of a given culture are nowadays, along with the greater variability of the observed systems, extremely varied and more sophisticated (Ramazzotti 2010, 88-126). The analysis of the metric frequencies of the attributes was conducted in this way to select trends, distributions and correlations in order to structure the artefacts, and the first histograms represented their formal characteristics in terms of modes and frequencies. In the same manner, the analysis of the nominal frequencies, performed through chi-square test of contingency tables, allowed the recognition of association matrices of two or more classes and the verification of whether a given decoration on the surface of a type of container was random or not.

The necessarily accelerating increase in the homogeneity of the classes and the presence of documents with strongly variable attributes (many of which shared by different artefacts, but none necessary or sufficient to distinguish or characterise them) was incorporated into the concept of "polythetic" groups, which is a key concept because it gave rise to specific research on the tools that are the most appropriate to highlight the *similarities* and *differences* which could structure composite and/or highly specialised production.

Nevertheless, the recognition of these qualities (analogies and differences) in the material culture follows the application of those methods in the psychological research, in order to recognise such functions of the cognitive process. In the first cumulative analyses, which were studying the growth of the level of technology in parallel with the evolutionary process, the percentages of artefact types were associated with the cranial capacities, in order to explain the presumed symmetry between the growth of the functional complexity of a given implement and the man's evolutionary growth, essentially understood as an adaptive growth, in other words a growth caused by the necessary acquisition of technological experiences (Leroi-Gourhan 1977).

In the same way, the methods of multivariate analysis, factor analysis, automatic classification and Principal Component Analysis intended to show the *structural* nature of variability present in the class, both to enable a future more precise comparative exploration and to draw its unique and irreducible associative root (e.g. Moscati 1984). This attempt to trace the origin of the class in order to redraw its relational structure was, on the other hand, equivalent to the first experiments which were performed in analytical psychology to outline the human ability to structure reality into similar and different (Sternberg 1985, 19-27), and indeed those very first studies using differential logic to understand intelligence gave rise to the hypothesis of applying techniques such as Correspondence Analysis in order to reduce the high level of variability of the recognised cultural traits into a limited and more controllable number of factors. The economic behaviour of a culture presupposes the principle of the archaeological site as an entity defined by a group of measurable geomorphological, stratigraphic and morphometric values. Accepting this principle, many territorial analyses applied statistical methods to document the existence of valid laws able to explain the different economic behaviours.

The first analyses of this type were performed to verify how the settlement structures, defined in graphical models of spatial structure, can be outlined in consistent logical networks, which would be transformed automatically by changes in the geometric measurement of their respective areas of influence, in their reciprocal linear distances, in the "weight" applied to the group of nearby settlements and, finally, in the relationships between distances and sizes of the centres present in a defined system.

These automatic changes, which evidently transform every organisation of the territory into a different settlement model, were then illustrated by the application of more complex rules which all aimed to define the structural characteristics of the transformations, considering them determined by the interaction of either two variables, i.e. the size occupied by the site in the hierarchy and its distance from the other nearby centres, or three variables, i.e. the size, distance, and influence on the region. Among the most appropriate tools to activate this process, the so-called Thiessen Polygons have had a strong impact since the early 1980s. The theory, originating with René Descartes and then mathematically developed in the 19th century by Johann Peter Gustav Lejeune Dirichlet and Georgij Feodos'evič Voronoj, provides for a grid of polygons to be drawn around the set of distributed points – each sides of the polygon is formed by the perpendicular line passing between the minimum distance of two points.

The calculation of the area of each polygon is understood to be indicative of the macroscopic differences in the distribution of the points in that space; in any case, since this grid does not take into account the high variability of factors of the three-dimensional space (e.g. geomorphological obstacles) and their temporal differentiation (e.g. the dynamics of attendance of the territory), the automatic use of the grid can produce questionable results. The measurement characteristics of the polygons have indeed recently been redefined, and a "weighting" system has been proposed, which is based on moving from the perpendicular to the distance between centres, therefore no longer passing between the midpoints, but fluctuating proportionally to the difference in size between sites. In the so-called X-Tent model, therefore, the calculation of the "weight" (in other words) influences every site on its surroundings.

The application of these models has become typical in research on a territorial scale, but they have also been used to simulate and compare landscapes of power on a much larger scale (Level, Renfrew 1979; Renfrew 1984). The automatic change in the transformation of a settlement structure did not, however, offer the chance to identify which ones of the functions activated in the structure were able to transform the settlement landscape. From this limit, a more ambitious attempt emerged to further summarise the recognised frames in order to ascertain which system of economic rules was the origin of the change. Once the syntax of the main relationships between the sites of a structure had been systematised in a theoretical list of associative constraints, could the exploration of the *rules* held to be at the base of the change began. Rules which – initially – were using the principles of urban economics, first of all that founded on the interpretation of the relationships between production and transport cost, then between production, cost and geometry of transportation.

The latter (which was a true geographical theory of optimisation in the early 1930s in Germany), the called Central Place Theory (CPT), is still widely applied in research into urban economics, economic geography and territorial archaeology. CPT presupposes that an organised distribution across a territory is based on at least two macro-categories of settlements – one composed of the most important in terms of size, population, availability of services, commercial structure, etc., and one composed of the less important ones. The second group of settlements will tend to arrange themselves around the first depending on the ease of access or administrative control, until they form a homogeneous hexagonal lattice. According to this economic theory devised by the German geographer Walter Christaller (1933), the centres' distribution in a given territory is regulated by "Principles", a logic by which optimising industrial production, reducing the difficulty of travel and transport and minimising production times and methods are inevitable. In this sense, CPT can be considered a deductive model founded on a series of postulates and axioms, and in this same sense it has been widely applied in the area of European and US territorial archaeology since the early 1970s (Johnson 1972; Clarke 1977).

The analysis of the economic relationships between settlement sites did not, in any case, have to be limited, or reduced to the presentation of those optimal operating rules that the systems would aim at obtaining and that would be lying beneath their diversity. The problem, encountered more than once, was the poor consideration of the geomorphological aspects of the territory, which *de facto* involve a constant deformation of the theoretical model (hexagonal lattice) into more or less rhomboidal or trapezoidal shapes, making highly questionable the causal explanation of the structural change. Moreover, as far back as 1972, Clarke's Gravity Model simulated the intensity of the economic relationship between multiple settlements by defining an expression directly proportional to the product of the activities performed and inversely proportional to the cost of transport, in order to reinterpret the meaning of the economic relationship in relation to the transport costs and the direct productivity variables, present in the classic CPT formulation, but subordinate to its rigid spatial geometry (Clarke 1972a, 7).

The limits of considering the complexity of the relationship behind the morphometric parameters of the sites and landscapes were soon perceived; indeed, the first ecological models can be understood as an attempt to shift the observation towards greater spatio-dimensional formalisation of the (theoretical) structure, which could support more refined analysis of the (adaptive) mechanisms originating the locational choices and the same socio-cultural transformations. As such, these mechanisms have later always been presented as highly complex and non-linear phenomena which can be simulated on an ethno-archaeological level, by comparing the spatial action of modifying, changing and structuring the landscape which is typical of the living cultures; on an anthropological level, by identifying osmotic and/or reciprocal relationships between groups, or in other words a spatiality that is no longer just diffusive and sequential, but able to alter the geometry itself of the occupation; on a social level, by predicting the settlement developments by applying distribution curves, e.g. normal, originally employed in the correction of geometric measurements; and finally, on a demographic level, by interpreting the influence of different conditions on the theoretical and regular growth trends.

The more culture is studied in biological terms, the less it is reduced to an automatic phenomenon, and the reasons for its specific spatial distribution are pursued with more sophisticated simulations which tie the occupational process to the action of specific algorithms (Foster 1989; Allen 1991, 1998; Chippindale 1992, 251-276). Moreover, some of the more recent researches, aiming to experiment with connectionist computational models, employ the formal and conceptual elements proper to Cellular Automata to simulate the dynamic complexity of the locational choices using bottom-up logic. The emphasis in these cases is not placed on the evolution of the settlement system but rather on the learning capacities of the automata; their ecology is wholly artificial, but the choice of their location does not just depend on the environmental input but rather on a complex relationship connecting sites, environment and experience.

We must remember, however, that the rules of transition driving the location choice and the organisation of the territory are a hotly debated topic; in isolated cases, indeed, on employing integration between Cellular Automata and Neural Networks, the use of predictive functions is preferred, such as the normal (or Gaussian) distribution curve which provides a prediction of the trend as the mean and standard deviation change, using the limit theorem to minimise systematic and/or accidental errors. In archaeology, it has been widely and indiscriminately used both as a tool for the correction of geometric and topographic measurements and as a support for the verification of theories about the economic and social behaviour of cultures (Rogers 1962; Renfrew 1984).

3.2 *The inductive inference*

The analyses and methods using the inductive inference tend «to *generate* Rules from the repeated observation of a Case», providing a formalisation (model) of the case which identifies and selects the rules and allows to postulate other rules. In experimental archaeology, these rules are stated as mathematical operations (equations, functions, algorithms) which offer reasonable theories on the causes which are behind the relationships between variables and which can generate other significant relationships. The fact that each cultural context leaves the traces of a series of actions produced by the ancient man on the territory, and that this evidence is the only *trail* left that allows us to recognise those same actions, has strongly supported, in the Humanities research, the adoption of the circumstantial paradigm, better known as the hypothetical-deductive method.

The analyses, procedures and models based on this euristic method always tended towards the formulation of a theory or a series of theories which could reveal (or *justify*) the events. Nevertheless, while the first models purported to formulate theories based on the comparative observation of the cases, or by comparing "the case" recovered with cases of living cultures, over time a method was refined which aimed to transform information into *evidence* and evidence into the apex of a network of semantic associations. This inference is particularly exploited today, when the intention is to present reasonable theories of the spatial and temporal data structure – in the first case, the models aim to supply a possible view of the physical causes of the materials distribution; in the second case, they generate a structural framework, generally phylogenetic, which observes the constraints imposed by the spatial structure.

The search for informative distribution rules therefore led to a long debate in spatial geography, territorial archaeology, ethno-geography and ethno-archaeology, but it currently seems to have been reduced to the suggestion to use models which are able to select which "physical" conditions are behind the formation of the deposits and which "theoretical" constraints are behind the adaptation. Today, informative distribution models can be understood as any process able to facilitate a widespread comprehension of the information, by indicating where it is significantly lacking in intensity and by predicting some of its structural typologies.

These models converge on the selection of transverse (physical and theoretical) rules which allude to the existence of a "natural" behaviour of the material culture and categorise those peculiar "adaptive" behaviours of the group (or groups) which use them. Despite the fact that over the years this commitment has produced enlightening hypotheses on the associations able to connect the structure of spatial data to the group adaptation, today there is a tendency to not overstate the "transversality" of the system but to examine rather the complex physical, mechanical and natural causes.

In the micro-space, on the other hand, the search for spatial articulation rules has, over the last decade, made use of generative models able to outline (or assimilate) the occupation and, in particular, the construction of intra-site architectural spaces, direct and inverse, in which "nuclear" elements are added or removed by following certain constraints (or rules). These constraints (or rules) differ depending on the case, but they all aim to express the complexity of a class of spatialised attributes as if they were generated by a resolutely oriented relational process; either progressive or inverse, these relationships always replicate a linear evolutionary trend.

Given their simple behavioural mechanism, generative models find widespread use in archaeological and geographical research and have been used in the past both as tools for the automation of archaeological hypotheses at a given level of complexity (Doran 1972), and as technical tools which identify the steps of each specific evolution or regression of the typologies (Chippindale 1992); on rare occasions, in any case, the interpretation in studies thus designed comes from a shared linearity of the process for investigating the action of variables on logotechnics. It is nevertheless interesting to observe the growth of the applicative research integrating Geographic Information Systems and ANNs (Black 1995; Openshaw, Openshaw 1997; Fischer, Reismann 2002; Zubrow 2003; Ramazzotti 2013c).

The network of semantic associations drawn from the physical relationships of the geological stratigraphy is also behind those models aiming to select the most suitable rules for the relative temporal placement of the document (Fig. 6). On the other hand, the position of the document in its stratigraphic level is the best evidence for defining it in terms of relative chronology. It is evident if only we observe the many experiments which are performed today, both to formalise the stratigraphic logic and to use IT techniques to refine the procedures for referencing the elements located in the archaeological deposits. Therefore, the desire to save all the evidences from the destructive mechanics of the archaeological excavation also favoured complementary analysis to the usual ones, which could provide integrated management of the position of the document in space and time and, in this manner, feed the chain of hypotheses and deductions that are necessary to perform any historical interpretation.

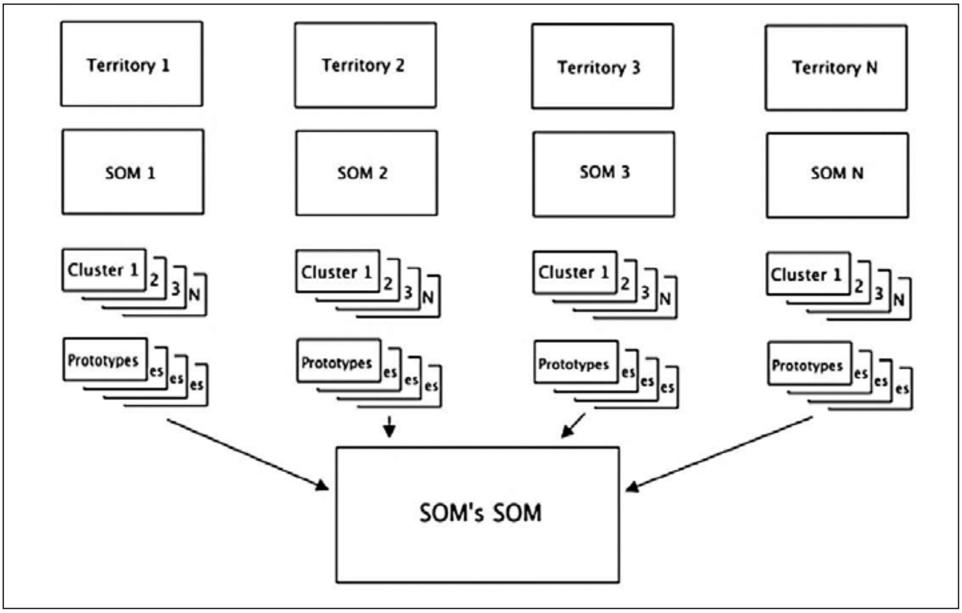


Fig. 6 – Blocks diagram of SOM's SOM procedure. The huge amount of spatial data generated by software GIS development, the increasing number of geographic computer applications available, the computerization of a large amount of information sources, and the availability of digital maps have increased the opportunity and need for the utilization of methods for spatial classification, for both research and applied purposes. Artificial Neural Networks (ANNs) can be used to develop a classification procedure which blends traditional statistical methods with a machine learning approach, allowing the system to iterate over a collection of datasets until patterns can be learned and realized (Londei 2013).

The highly variable nature of the features present in some classes of artefacts poses the problem of inserting them into a classification, able to sub-classify into other classes relevant in the relative spatial and temporal placement of the artefacts themselves. For these reasons, the first "combinatorial models" were implemented; through the formalisation of the observation into decomposition rules, founded initially on the presence/absence relationship, these models would offer a structured description of the spatial-temporal object through calculation algorithms. But although this decomposition could have been sufficient for a reasoned deconstruction and reclassification of the highly specialised artefacts, it would not have added anything new to their relationship with other variables of their original archaeological context.

This possibility was offered to experimental research precisely when it was decided to manage the contextual issues in an integrated manner through a more general theory, which allowed the comprehension of the action applied by a variable on the system of connections, connecting it to further important characteristics of the context, these variables being similar to those of a constructed mechanical system or to those of a known natural one. Therefore, three paths were available to recognise the functions fulfilled by each given archaeological and/or geographical variable in a specific context, systematically structured following the analytical approach: to interpret the entire mechanism as if it was a theoretical and always functioning machine, with known relationships between the various elements; to suppose that each cultural and/or natural system has a biological life characterised by complex moments of growth, withdrawal and collapse; and to find the natural probability of the connections between the various elements of the system.

The first path would offer an optimal and theoretical presentation of the syntax regulating the various parts of the system. A presentation by which the same variability of the aspects of a context, in order for it to be able to function mechanically, would be defined *a priori* (Systems Theory); in the second path, the system of variables of a given context would be superimposed on the functional cycles of the biological systems and therefore undergo their same growth rules up to the point of collapse (Catastrophe Theory); in the third, the probability of the associations between variables of the cultural system would be codified, and their behaviour simulated with probabilistic network, this is the case of, for example, the Bayesian networks (Gardin 1987; Clarke 1994; Bintliff 1997; Ramazzotti 2010, 171-198).

The contemporary archaeological research does not limit itself demonstrating the principles of complexity in cultural, economic and social systems, slowly starting, since the early 1960s, to work together with radically different disciplines, for instance Cybernetics, which, by their own theoretical admission, live and develop for analysis of and experimentation on the rules of complexity (Ashby 1964; Hall 1989; Gehlen 2003, 46; Rogers, McClelland 2004). This approach to other fields prompted the construction of a wide range of models which select the causes of complexity in systems and, therefore, attempt to represent their origins. It should be noted that the working together of Archaeology and *Κυβερνητική* (Cybernetics) was neither sudden nor revolutionary (nor even linked to the advent of the American New Archaeology); it was rather the first, enlightening attempt to compare archaeological contexts with dynamic systems which promoted the inevitable intersection of the two different disciplines.

As in mechanical systems, the relationship between variables of a given context could therefore be described not only in recognisable geometric forms then redefined into theoretical maps causing a distinctive activity, but also in maps from which those Rules able to transform their internal connections and their organisation could be selected – feedback, attractor, and dynamic equilibrium, which had already been studied by "Mechanical Intelligence" even before Cybernetics. This would, on the one hand clarify the limit of automatic operation of the systems and, on the other, lead towards the replacement of the mechanical (and linear) nature of the relationships with the physical-biological (non-linear) one (nature) of the connections.

The feedback rule has been selected, reviewed and discussed in many models aiming to represent the complex formation of the State; the recognition of attractors in many models aiming to recognise the homoeostasis of social and economic organisation in a chronologically and spatially localised state, and, moreover, the dynamic equilibria in many others which emphasised the anomalies of a given territorial structure (Waldrop 1993; Page 2010). Models which perform analogical inference, «which *form* Hypotheses based on the comparison between Cases», are founded on, amongst others, analogies or similitudes, through which the intention is to grasp the logic of a particular phenomenon in relation to the better known operation or directly observable. In this sense, working them out requires a "symbolic capacity", in other words the ability to grasp the whole from the allusive evidence of the part (Gehlen 1983, 207-208).

3.3 *The analogy and abductive inference*

The models which use analogies have dealt with the relationship between the physical scattering of the materials in their contexts and the operation of the cultural systems which had produced them; the relationship between the behavioural variables of the cultural systems and the formal variables of the major economic theories; the relationship between the perceptions of the objects and their environment and those of the operation of memory and perception. The models which establish a comparison between Culture and Environment aim to present the transformation of cultural phenomena as being dependant on physical and biological laws which can be checked scientifically; but while most of this processing reaches the environmental determinism – a term which, indeed, highlights how a group of natural causes can condition the structural change of the same social organisations – the confidence that these transformations could instead relate to the human action on the resources is owed to the Department of Prehistory at Cambridge, known as Palaeoeconomy (Higgs 1975).

For the founder Clark, indeed, the comparison between the physical-biological laws which control the characterisation of the environment and the cultural-economic laws which govern the social structures would lend itself to the construction of an integrated and global transformation model in which they would all interact; the discipline would therefore be responsible for the job of reorganising them in other different theories (local and contextual) of the individual processes (Fig. 7). This model which, starting from a common base of principles, would allow hypothetical theories of the individual

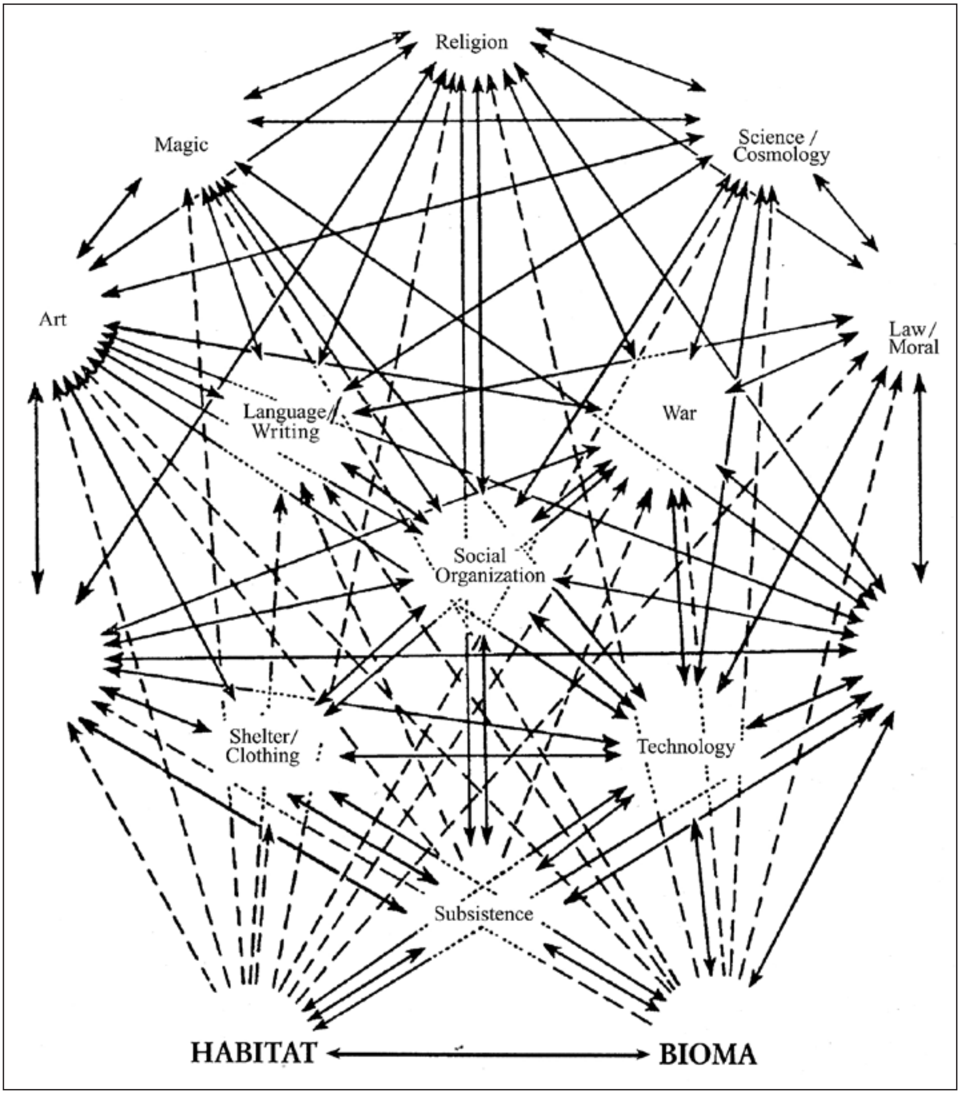


Fig. 7 – Diagram of interactions between Habitat and Biome. In the interpretation of the British archaeologist both ends of arrows imply dynamic and reciprocal relations. This is one of the earliest and most notorious attempts to deal with socio-cultural organizations as integrated and parallel to those present in the environment (Clark 1992).

economic developments to be established, would be represented in a spatialised and structured system in which social organisation would occupy the centre of a network of connections (direct and inverse), with most variables depending on it or which could simply characterise it; a system nevertheless constrained at its base by the reciprocal relationship between Habitat and Biome (Clarke 1999).

The model generated by keen comparison between physical-biological laws of natural transformation and cultural-economic laws of social transformation, and spatialised as a complete system tied to interdependent relationships would therefore offer a precise and general theory of the economic and cultural operation regulated by systemic principles of structural equilibrium, or of homoeostasis, as explicitly stated by the Australian archaeologist (Clark 1992, 162). As we have observed, the analogy between Culture and Environment, decoded by Clark into a systemic model, had a very large following in archaeological research aimed at reconstructing economic processes, but it was also relevant for introducing the concrete possibility of also comparing the principles regulating cultural transformation with those controlling natural transformation. This analogy could be conventionally defined as being second level, and its analytical potential was noticed rather early by D.L. Clarke.

Analyses and methods which follow abductive inference generate theories on these cases from the possible results and offer all those representations (models) which outline a theory of the cultural, social, political, economic and cognitive function, looking for their foundations outside the perimeter of strictly archaeological analyses, methods and techniques. These theories can be displayed as "closed systems" tied to a precise logical structure, or as "open systems" characterised by a dynamic combination of connections, but in both cases they express a global and integrated interpretation of processes, events and facts; they exhibit the set of relationships that these three "elements" of the story have with the world of the present and the past; they change their morphological structure in relationship to the quantitative and qualitative growth of the documentation.

From the results obtained in the biological area through the study of the rules of operation of the selective process (Edelman 1987, 1988, 1989), some archaeological research is starting to update the classical body of tools of linear and multi-linear neo-evolutionist theories and to head resolutely to set up a new semantics of cultural function. The attempt to deconstruct the functional complexity of the archaeological documentation is indeed encouraging some experiments on "generative grammar" which can be related to it, which is understood as the codes of a given spatial and temporal structure, necessarily constrained and therefore subject to the same rules of the selection process ingrained in the theory of evolutionary biology.

Other, even more specific, studies examine the processes of cultural diffusion, aggregation and classification through the models of coevolution, thus identifying how they fulfil themselves by the interaction between genetic evolution of species and the effect of human action in influencing the exploitation of resources.

Going beyond the limits of analysing archaeological cultures as concrete expressions of their documents and the transformation processes with the mechanical logic of human action on the environment, or conversely of the conditioning the environment might have on it, the possibility also stands out to define cultural diversity on a genetic basis, to interpret its slow transformations by making an equivalence between the concept of "population" and that of "culture" and that of a spatial circumscription for it which is not just geographical, ethnic or linguistic. This diversity, which has many different contours and nuances only apparently recognised on ethno-linguistic foundations, necessarily subject to the possible manipulation of old and new ideologies, foreshadows a map of the ancient human genome, predominantly useful for medicine, but also sufficient to make the spatio-temporal relationships which have always been focused, in one way or in another, on the critical distance taken in relationship with some more complex principles of equivalence, such as the classic one between "culture and typology".

The results obtained concerning the social complexity of the mechanisms which regulate cultural relationships did not only produce a reduction of the classical application of Systems Theory to archaeology, but also, at the same time, a trend of the discipline developed which, by updating that same theory with the aid of the new mathematics, aims to define some characters which predate cultural complexity itself and which, in the same way, can be examined again in light of that renewed theory. As already highlighted, beginning in the 1980s the attempt was made to dissolve the intrinsic rigidity of the regulatory mechanisms of the Systems by replacing the linear Input-Output function with some rules of anthropological relationships, considered more flexible in documenting the structural transformation of cultures (Peer-Polity-Interaction), or by clarifying the natural and biological direction followed by each system (Catastrophe Theory). But since the early 1990s, that "critical" path aiming to detail these limits and, therefore, to identify the mathematical rules which predict the ancient functional use of the objects has been undertaken (Rough Set Theory).

Some studies examine the dynamic oscillations of the processes of territorial organisation, employing models which organise themselves and which, as other cases present in nature show, tend to reach a stationary state of *equilibrium*, beyond which they transform themselves. Other simulative studies trace the problem of location choices, traditionally dealt with through the principles of urban economics (agglomeration, accessibility, interaction and hierarchy), back to the multiplicity of choices and the constraints determining this.

The self-organisation of highly complex structures and the multifactorial nature of the choices influencing the territorial form of the systems are all recent phenomena which inevitably act to construct a new semantics of cultural transformation. Indeed, these phenomena require to overcome the obstacle of an interpretation which reads the purely "human" construction of ever-more complex systems to understand the cultural transformation and advance the illusion (or the ambition) of paying more attention to those phenomena, present in nature, which do not require external inputs to act dynamically and transform themselves. In the same manner, they require to cross the limit of the "mechanical" construction of organisational complexity, in which an Instruction (or a few fundamental relationships) would be sufficient to transform the system in order to observe, classify, formalise and organise other rationalities of the locational choices.

Some of the most recent archaeological studies have been inspired by the continuous results obtained by contemporary Semiotics, Semantics and Logic in shaping, deconstructing and reconstructing the world of meanings of structures, signs and symbols, as well as their internal constraints and the rules governing their perception and communication, to further theorise other information analysis procedures, propose other forms of their communication and generate other theories of their combination.

These are also expressed in models, more structured than the ones we have already dealt with, because those are summarised within them. As far as the data analysis is concerned, as we have seen, Clarke, with the definition and elaboration of polythetic entities, had already supplied categories for learning, translating and transferring technical experience, seeing them in the grammar of the first semantic-perceptive models which were still, in the late 1970s, largely structuralist. This first step towards a logic of the sign transmission – which has been improperly excluded from the critical historiography – is today, indeed, right at the roots of that search for techniques and models suitable for transforming the documentary archaeological situation into structures, codes and messages, both written and visual, which can, in a certain sense, distinguish it.

Jean-Claude Gardin's constant attempts to prepare the logic of archaeological theoretical-inferential reasoning are, indeed, operations destined to yield an anatomy of the perceptive mechanisms which are behind historical knowledge and its inevitable reworking (Moscati 2013). This anatomy of the human historical reasoning wishes to display all the strength of the subject, the arbitrariness and the conditioning of meaning and, for this reason, has always offered itself to elaboration and simulation (Gardin 1970, 1980, 1987, 1989, 1996a, 1996b). Labelled as a speculative and sometimes ineffective attempt, this trend has, on the contrary, painted a picture of archaeology as logical-scientific research, always open to enquiry, aiming to build a "metalanguage" which expresses its most profound nature.

As far as the modalities of scientific communication are concerned, on the other hand, many archaeologists draw inspiration from the semiotic communication theories to design and exhibit other forms of research. Thus, for example, Colin Renfrew attempts to overcome the purely descriptive and analytical obstacles of investigation, in order to relate the complexity of the archaeological reasoning through the transmission of aesthetic experiences which organise new suggestive and effectual descriptions of the discipline, without, however, denying its internal order, its syntax, the organisation of work and the costs which, he presumes, are useless, boring and uninteresting details for the public as they are for specialists.

More structured, on the other hand, is the network model proposed by Hodder, for whom a horizontal circulation of archaeological information, established from a non-hierarchical, co-operative and collaborative work set-up would combine perfectly both the workable metaphor of IT networks, which are able, with many nodes and no centre, to transfer the complexity of information, its frequency and its relativity, like a metalanguage, and the literary metaphor of archaeology as narration, able to exhibit both the plurality and the same antimony as well as evaluations concerning the given object, as a never unique nor conclusive book written about.

3.4 *The connectionist inference*

But above all, the results obtained, together, in the disciplines of Semantics, Semiotics, Logic and Neurobiology, gave rise to different theories of the so-called "cognitive function" which were gathered first by Analytical Psychology and, only later, by Experimental Psychology. The contact between Archaeology and Cybernetics, already identified by Clarke as central in order to let archaeology abandon its aura of innocence, is not therefore a purely generational fact, but the product of a *wonderful* intuition, through which the English archaeologist intended to reconnect the abyss which had taken form, essentially due to the effect of the historical-cultural approach, between the Humanities and the Sciences, and in this way to offer a new category of meaning to the same definition of archaeology as "human science" (and it is not by chance that today we group it with the Social Sciences).

In the late 1960s, as we have seen, Cybernetics was, in any case, simply understood as an extension of Systems Theory and Artificial Intelligence, then nascent, effectively representing the pioneering technological illusion of reducing the function of the logic of knowledge to a formalism which could be managed with that theory. Nevertheless, while initial research in Experimental Philosophy used guinea pigs as if they were automatic machines and applied multifactorial analysis to trace the differentiability of intelligence, in the 1950s Neuroscience began to disown the paradigm of a brain regulated only by the modularity of electrical impulses (Oliverio 2004, 22-23).

The division of the observed world into classes and forms (*Gestalt*) then began to be gathered into more complex models which attempted to integrate the awareness that some perceptive functions were not simply calculable, predicted or predictable actions or functions with the necessary linearity of automatisation in "naturalising" the cognitive function (innervating the experience in the elaborative process of the synapses between neurons). But the Artificial Intelligence inspired, instead, by "theoretical" Neuroscience research and by "practical" Neurobiology research, in other words inspired by the interpretation of the cognitive function as a certainly more complex expression of a relation between the physical and irreducible elements of the brain, appeared only in the early 1990s.

Today, its foundations and origins are still discussed, but it is at least unanimously recognised that its advancements in recreating some segments of knowledge trace back to that area of the Neurobiology of memory which, having risen in radical opposition to the more ancient and traditional behaviourist school, was then defined as "connectionism". Connectionism is understood as a theory born inside neurobiological research on natural intelligence and the reproduction of an artificial intelligence; according to it, the brain is not just ascribable to a system of rules and symbols, but it is composed of the operation of simple and non-intelligent elements known as "neurons", whose connections (synapses) express properties of coherence (Fig. 8).

The connectionist approach represents, in this sense, a reaction to the "behaviourist" and "representationalist" theories which did not tackle the study of Artificial Intelligence based on the dynamic and connective relationship between the neurons, but interprets the logic of its operation in the mechanical Input-Output flow (Fodor 1975; Minsky 1986; McClelland, Rumelhart 1986, 1-20; Ackley 1987; Fodor, Pylyshyn 1988; Feldman, Ballard 1989; Ackley, Littman 1992; Fodor 1999; Marcus 2001; Clark, Eliasmith 2002; McClelland *et al.* 2010). In international archaeology, it was chiefly Jim Doran's research which supported the applicability of this logic for studying social systems; of particular importance was the insertion of Multiple Agents System Theory (MAS) and Distributed Artificial Intelligence Theory (DAI) as the foundations for building dynamic socio-cultural models (Doran 1970, 1996a, 1997).

In particular, the second theory (DAI) aimed to conceptualise the structure of artificial scenarios to combine the representations of the individual cognitions of every agent and verify the qualitative characteristics of the birth of social hierarchies in the French Palaeolithic communities (Doran, Palmer 1995, 103-125). Since today any analysis of the principles regulating memory, learning and classification (that is to say the fundamentals of all Theoreti-

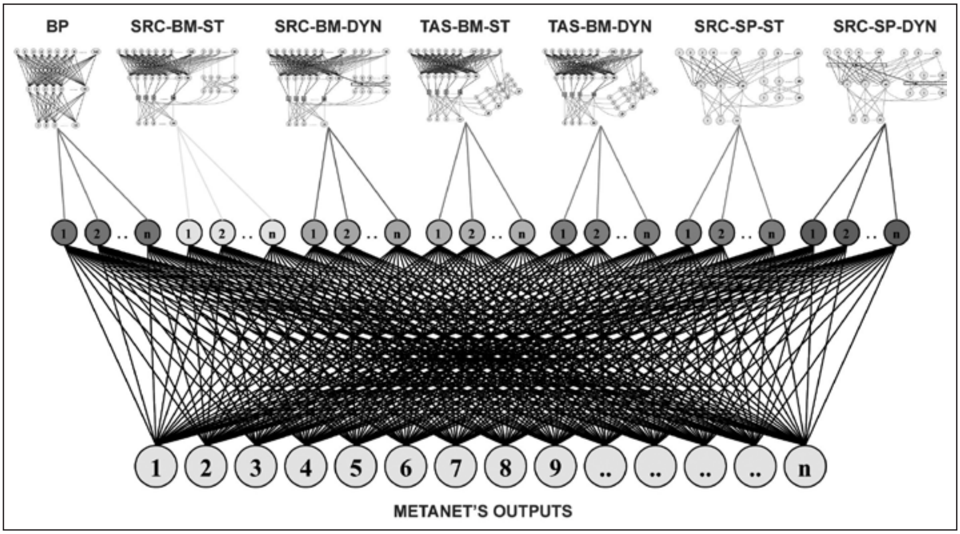


Fig. 8 – Metanet Topology. Between 1994 and 2008 Semeion researchers conceived and developed a series of Meta-Classifiers based on some common traits and called them "Meta-Nets." All Meta-Nets have typically similar neural network architecture; certain input nodes are the whole outputs of all composing classifiers, and certain output nodes are the output classes of the classification problem (Buscema, Tastle, Terzi 2013).

cal and Experimental Archaeology) depends on this border. Back in the late 1990s a series of studies was proposed, in the archaeological field, which had already perceived the epistemological relevance of the connectionist models (Ramazzotti 1997, 1999a, 1999b).

4. Encoding cognitive complexity through the Artificial Adaptive Systems

Currently, less than a decade after these studies, we can already distinguish at least two different directions: the first aims to explore the high level of complexity of the archaeological processes, structures and systems, supporting the semantic instrumental value of the Artificial Intelligence in rewriting a General Theory of Archaeology; the second, instead, shows and emphasises all the statistical instrumental potential of the same models which are in reality replacing the more traditional mathematics of classification.

4.1 *Systemic complexity and Artificial Neural Networks*

Most researches relating to both directions make use of the principles according to which every cultural expression is the reflection of conceptual and cognitive human processing (in the real, or not random sense), and the human conceptual and cognitive expression can be reproduced through the construction and simulation of systemic and mathematical rules (in empirical, not dogmatic terms). Even though they leave open the whole problem of how non-calculable factors (such as emotivity) can alter any state of equilibrium, the first Networks, which are physical architectures of the complex relationships between the irreducible elements of the brain, historically represent the point of reference of the two analogies – they are inspired by the biological model of knowledge (hence neural) and represent, in a structured manner, some of their aspects (or segments), which can be empirically checked, through a great variety of techniques and models (hence artificial).

In the psychological-cognitive area it has by now been demonstrated that the organisation of reality by each individual does not just depend on the action of the environment on their formation, or (*vice versa*) only on the action of their choices on the environment, but that rationality is understood as functions of experience. Among these functions of experience, neuroscience studies memory, first in its evolutionary dynamic, then as a biological model and finally as the dependent nature of genetics. Observed as a biological model, memory is a product of the nervous circuits subjected to an experience, and in the area of dynamic mathematics it can be simulated in regulated (or self-regulated) systems. Associative Memories are, in effect, among the first processing mechanisms which learn by taking rules from complex systems and, as such, they demonstrate to be capable of finding possible solutions to non-linear problems.

An archaeologist studying the complexity of archaeological processes through these models investigates the relational dynamics between the classified variables of a given context in the same way as a psychobiologist studying the complexity of the perceptive-analytical process of an individual (or a group of individuals), and a neurobiologist exploring it on an empirical level. Rather than calibrate suitable and expert tools which repeat the relationship between variables like the one present in connected parts of a machine, the archaeologist will therefore aim to trace the possible, nuanced and non-linear rules of their operation and will never obtain a single result, but rather analytical surfaces (hypersurfaces) which will lend themselves (with humble, controllable repeatability) to historical-archaeological interpretation. In the psycho-cognitive field it is well-known that the perception and organisation of reality by an individual increases and changes in relation to the quantitative and qualitative growth of the information and messages they exchange and receive.

Phenomena such as orientation, which in psychobiology are also considered adaptive phenomena (i.e. depending on learning and memory), can be simplified into highly complex and structured systems which change dynamically in relation with the increase of the information. Some experiments performed with Cellular Automata demonstrate how these can identify the rules which connect different groups of data and organise their adaption, by transforming them in relation to that given quantitative and qualitative (but nevertheless dynamic) growth or regression of the information (or the constraints).

Their first applications to archaeological spatiality are therefore to be understood as simulations destined to explore, recognise, classify and typify the different spatial forms that a behaviour assumes in relation to the increase and decrease of the information (instructions) received by it or subtracted from it, and in this sense it is today guiding the application of neural models to the topology analysis of the forms of dynamic adaptation (Buscema, Breda *et al.* 2013; Buscema, Sacco *et al.* 2013; Buscema, Tastle, Terzi 2013).

4.2 *Artificial Adaptive Systems and archaeological thought*

The archaeologist studying the complexity of the archaeological processes through such models therefore intends to investigate the forms of the adaptation in the same way as a psychologist would investigate the perceptive-analytical reasons driving the organisation of a space (individual and collective), and a psychobiologist the physiological models which are at the origin of orientation; therefore, rather than building closed memorisation systems, which gather all possible information in a given context, this archaeologist would design systems which are as open as possible in order to receive the natural growth of information.

Since this open system would not only become another data typology, but would also become processable with other Artificial Intelligence models, its historical-archaeological interpretation would inevitably be subject to continuous updates, to the necessary extent. In the field of experimental and cognitive psychology, an individual's process of classifying reality occurs by effect of his capacity owing to the experience he acquired in operating summaries and generalisations; as such, the organisation of forms into categories of meaning is considered a complex phenomenon which provides for mnemonic and learning skills.

The Artificial Neural Networks which have been trained to trace those rules which structure a given complex system can also perform corrected generalisations on the system, redefining the system itself into other relational classes. Their first applications in the seriation of archaeological data – a classification which necessarily increases in complexity in relation to the increase in information – are therefore also to be understood as attempts to apply a given individual's adaptive skill and experience to organising the reality surrounding him. In the area of experimental and cognitive psychology, the predictive abilities of an individual depend on the dynamic behaviour and structure of the variables he has at his disposal to take on the solution to a given problem; this behaviour, therefore, focuses on a response which transforms the input information into highly structured surfaces, representing the form and substance of the observed reality.

The Artificial Neural Networks that are trained to trace the nuanced rules of a given complex system can construct a surface geometry of their learning, which changes in relationship to the qualitative and quantitative characteristics of the other stimuli received (Buscema, Breda *et al.* 2013). The ANNs trained to define the rules of a given complex system therefore offer a possible generalisation which lends itself, at a later date, to being interrogated using prototypical questions in order to delineate a given object of investigation in quantum terms, both by modifying the number and intensity of the inputs (simple interrogation) and by adding other possible (complex) ones, and observing how that representation (surface) changes its structure with each response. Their first applications to predictive archaeological problems are, therefore, to be understood as attempts to apply the diagnostic abilities of an individual to transform what he observes into a possible prediction of its function.

The archaeologist who simulates the dynamic behaviour of a Complex System through these Artificial Intelligence models intends to explore the configuration of the data (which has been learned) as an analytical surface, in a similar way to that of a psychologist investigating the perceptive-analytical processes of the predictive potential of an individual. Therefore, rather than describing the purely systemic complexity of a given context, the archaeologyst would aim to work on how that context was learned in order to interrogate it in a diversified manner and to trace every possible combination of it, thus providing a wide cross-section of historical-archaeological predictions of its state.

When *Analytical Archaeology* appeared on the scene of international archaeology, as it had happened to other essential scientific essays of the archaeological research, the English-speaking academic world, British and American, broke decisively in the evaluations (Chapman 1979). While for some scholars that work, that in the great archaeologist's expectations would have provided a central body to the theory of archaeological knowledge, became a kind of *simulacrum*, a new method of investigation, and, more generally, any proposal for other experiments, for others it would have remained just an unnecessary (and unacceptable) mystical brushstroke.

The first Italian translation of the *Analytical Archaeology* (Clarke 1998) speaks more than any other consideration on how this work – recognised as a prophecy – was perceived in Italy; in fact, there are no less than thirty years running between 1968, the year of its establishment, and 1998. Thirty long years of this century that was already leaving behind the historical-cultural orientation of the Italian archaeology, immobile to the generational change. We may then ask about the profound reasons of this delay, not to exhibit an opposition to the Normative Archaeology, a redundant and sometimes rhetorical critic of the American archaeology (always renewed), but only in order to understand those reasons and reopen that debate (Guidi 1998).

While Clarke was writing his theory, in 1968, in Italy the most distinguished representatives of critical thought, archaeological and anthropological historians were debating, in the prestigious scientific journal «Dialoghi di Archeologia», on the economic nature of cultures and on their specific political dimensions, aesthetic and symbolic (Ramazzotti 2010, 50-87). Far away from those premises that had been maturing into a unique and unmatched polyphony of historical, artistic approaches, renewing the same aesthetic and critical thinking as materialistic science, the debate on the morphology of the discipline and its ambition to become a General Theory was discussed by the Classical Archaeology and remained lively until the Gordian knot of the so-called "bi-front" archaeological thought was solved.

Today, after forty-five years, the adoption as well as the purchase of this volume are still singular. Arduous and written with a purely scientific vocabulary, *Analytical Archaeology* does not lend itself to be neither manual nor wise, even the intelligent editorial choice to frame it in a valuable series that aims in the first place to convey an image of archaeology as research and analysis; but archaeology as research and analysis for the broad public is still the symptom of a hazard, while the audience of specialists is often so sectarian, and in fact, hardly supports such a generality of the theme, such breadth and openness of discussion on empirical methods.

To remember the troubled history of the UK edition does not represent, for this essay, a nonsense: the balance of that reasoning; the accuracy of syntax; the ambition of an entire generation that grew up in that world so much projected into the future as attentive to dialogue with the past and with the tradition; the preconditions for a grammar of archaeology as the frontier not only of a General Theory, but of a Theory of Knowledge; the mention of the archaeological report of signs as communication are all elements that have inspired this work because they remind us that it is not possible to rebuild anything without a solid theoretical vision, without looking around, without being contaminated, without trying every possible solution.

The study of complex archaeological systems which can make use of the philosophy of Artificial Intelligence is, ultimately, a research project which evaluates the historical meaning of the relationships between archaeological documents as an essentially human construction which repeats, in this, a *strong* position of Analytical Archaeology, but updates it on the basis of the progress made by Cognitive Science, Neuroscience and Cybernetics in simulating the principles which regulate memory, orientation, classification and interpretation of reality. It is important to highlight that these models, unlike others, must make use of a precise encoding of the documents and take on an important role in the research only when the results which they produce become the hyper-surface to continue, update, refine or open the analysis itself.

Some considerations, after this brief, subjective and critical introduction to the history and use of the models in archaeology, are necessary before concluding this epistemological introduction to the volume. On one hand, these models, as the reader will have understood, almost always introduce new problems, even only for the fact that they are subject to constant re-examination. In this sense they irremediably prevent the closure of the research. On the other hand, even though today those research theories seem to be the most used in experimental and applicative studies, they should not be considered as forming a new paradigm since, like others, they respond to specific questions posed by the past.

If this was the case, if they really did represent a paradigm, we would indeed have to assume that those questions have been diversifying, developing and becoming more complex when, on the contrary, they always fit into the human categories of enquiry. What is changing, however, and decidedly, is the man's relationship with the technique which is now transforming natural reality from the inside, moving it onto a first artificial, then virtual plane, where everything, within the (desirable) limits imposed by ethics, is apparently possible. Our action on this new world is a field still to be explored on the historical, anthropological and archaeological level, but, by observing our models, we seem to perceive already at least the formation of different research areas into communication. The deductive models are headed towards a check or an anticipation of the possible context and they show today the desire, known to the discipline since its remote foundation, to orient themselves in the world which is created and replicated.

They spread out from underlying convictions, as old as the postulates and their axioms, they communicate a certainty that the referent can grasp in all their lucidity and rationality. The inductive models which continue to produce rules from observation arrange themselves (given their specific nature) in a more chaotic manner; they do not have those certainties, but they always live in the experiment, communicating the state of a new discipline, or one always in the course of renewal. Those which inflect analogy, on the other hand, resist and grow in this reality codified in signs and symbols precisely because they require "symbolic capacity". When it would seem that the *hiatus* which every analogy entails might fade away, here the metaphor, the similitude, the allusion appears.

In the *Time of Technique* it is even too predictable that the last perceptible limit is still that of the relationship (metaphorical, nuanced or allusive) between "mind and machine". Besides, in this age, it is almost instinctive to replicate the function of knowledge, to retrieve its origin and to rebuild a backstory for it. The models which, on the other hand, have searched for a place in the discipline by drawing their inspiration from other distant disciplines and at the same time from the theories which emerged and tried to explain cognitive function, would, in the *Time of Technique*, be absorbed by the recreation, even though minimal or "impossible", of intelligences, first the "ancient" and then the "new" Artificial Intelligence.

The other theory they would be inspired by is *reason as a tool* and, in the *Time of Technique*, this becomes the condition for interpreting and communicating the man's historical, archaeological and anthropological complexity.

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ABSTRACT

The study of complex archaeological systems with the support of the philosophy of Artificial Intelligence is a research project that evaluates the historical meaning of the relationships between archaeological documents, intended as an essentially human construction, reaffirming, in this way, the importance of Analytical Archaeology, and updating it on the basis of the progress made by Cognitive Science, Neuroscience and Cybernetics through the simulation of the principles regulating memory, orientation, classification and interpretation of reality. It is important to highlight that these models, unlike others, require a precise encoding of the documents and acquire an important role in the research only when the results they produce become the hyper-surface to continue, update, refine or open the analysis itself. In the *Time of Techniques* it is still too predictable that the last perceptible limit is still that of the relationship (metaphorical, nuanced or allusive) between "mind and machine". Besides, in this age, it is almost instinctive to replicate the function of knowledge, to retrieve its origin and to postulate a backstory for it. On the other hand, the models seeking a place in this discipline, by drawing their inspiration both from other dissimilar disciplines and from the theories that try to explain the cognitive function, would be absorbed by the recreation, even though minimal or impossible, of intelligences, first the Cybernetic and then the Artificial Intelligence. The other model they would be inspired by is reason as a tool and this becomes, today, the condition for interpreting and communicating the historical, archaeological and anthropological complexity of the human being.

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THE GENERAL PHILOSOPHY OF ARTIFICIAL ADAPTIVE SYSTEMS (AAS)

1. Artificial Adaptive Systems

Artificial Adaptive Systems (AAS) form part of the vast world of Natural Computation (NC) which is itself a subset of the Artificial Sciences. Artificial Sciences are those sciences for which an understanding of Natural and/or Cultural processes is achieved by the recreation of those processes through automatic models. We shall use an analogy to explain the difference between Artificial Science and natural language; the computer is to the Artificial Sciences as writing is to natural language. That is, the AS consists of a formal algebra used for the generation of artificial models which are composed of structures and processes, and natural languages are composed of semantics, syntax and pragmatics for the generation of texts.

Through each of these very different systems a level of independence is created; in natural languages the utterances of sounds are fully dependent on the time in which the utterances are made, but by representing those utterances with writing they become independent from time, for written documents (in the form of books, manuscripts, typewritten pages, computer generated Output in the form of both digital and hardcopy, etc.) exist outside the dimension of time. They exist in the spatial dimension. Similarly, the computer achieves independence from the physical system through the creation of a model. Such models are automations of the original system and permit one to study the natural/physical system at any time, even if the original system no longer exists.

An example of such a system is the active eruption of a volcano or the tremors of an earthquake. Through extensive measurements of variables a model can be constructed that permits researchers to recreate the original volcanic activity or earthquake in a completely controlled environment by which variables of choice can be controlled. By using writing as an extension of a natural language permits the creation of cultural objects that, before onset of writing, were unthinkable. Such cultural objects are stories, legal texts, manuals, historical records, etc. In a similar manner the AS can create models of complexity that, before the construction of computers, were unthinkable. Natural languages and Artificial Sciences, in the absence of writing and the computer, are therefore limited. But a written document not based on a natural language, or an automatic model not generated by formal algebra, are little more than a set of scribbles (Fig. 1).

In the Artificial Sciences, the understanding of any natural and/or cultural process occurs in a way that is proportional to the capacity of the

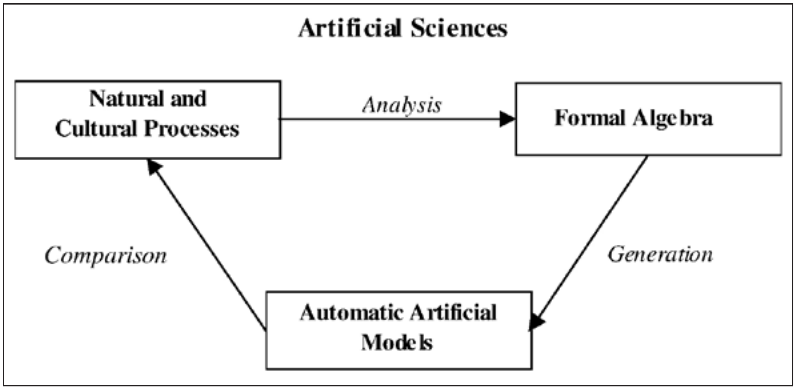


Fig. 1 – The diagram shows how the analysis of Natural and/or Cultural Processes, that need to be understood, starts from a theory which, adequately formalized (Formal Algebra), is able to generate Automatic Artificial Models of those Natural and/or Cultural Processes. Lastly, the generated Automatic Artificial Models must be compared with the Natural and/or Cultural Processes of which they profess to be the model and the explanation.

automatic artificial model to recreate that process. The more positive the outcome of a comparison between an original process and the generated model, the more likely it is that the artificial model has correctly explained the functioning rules of the original process. However, this comparison cannot be made simple-mindedly. Sophisticated analytical tools are needed to make a reliable and correct comparison between an original process and an artificial model. Most of the analytical tools useful for this comparison consist of comparing the dynamics of the original process and the dynamics of the artificial model when the respective conditions in the surroundings are varied. In sum, it could be argued that:

1) on varying the conditions in the surroundings, yields a greater variety of response dynamics obtained both in the original process and in the resulting artificial model; and
2) the more these dynamics between the original process and the resulting artificial model are homologous, we can therefore conclude
3) the more probable it is that the artificial model is a good explanation of the original process.

In Fig. 2, we propose a taxonomic tree for characterization of the disciplines that, through NC and Classic Computation, make up the Artificial Sciences system. NC refers to that part of the Artificial Sciences responsible for the construction of automatic models of Natural and/or Cultural Processes

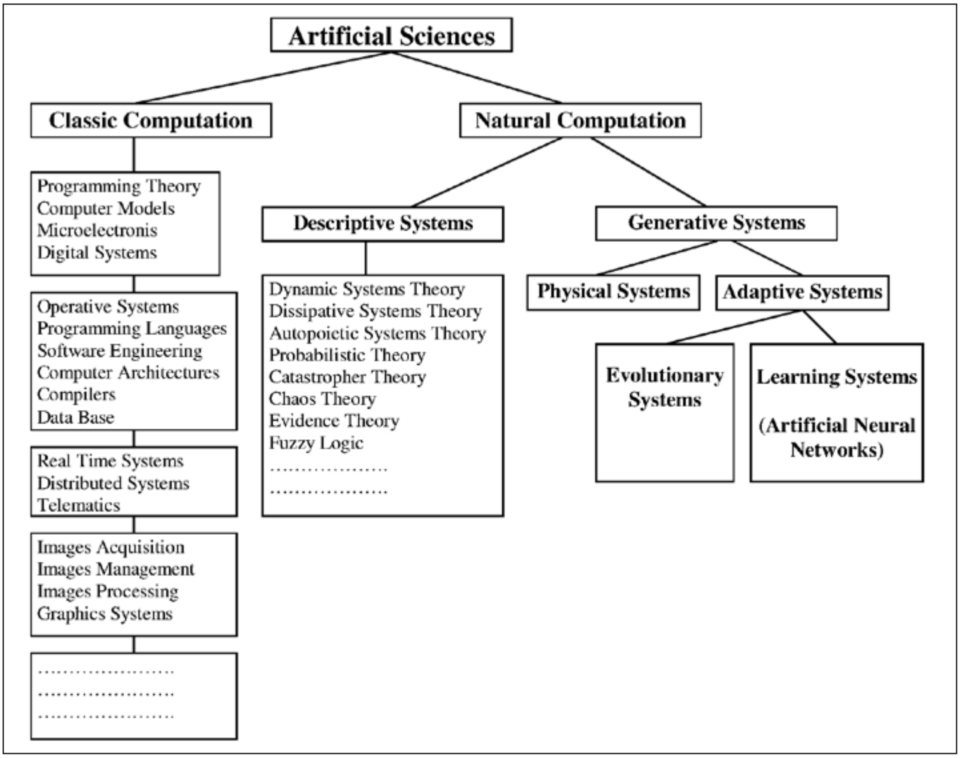


Fig. 2 – Taxonomic tree of the disciplines that make up the Artificial Sciences system.

through the local interaction of non-isomorphic micro processes. In NC, it is therefore assumed that:

1) every process is, more or less, contingent on the result of more basic processes that tend to self-organize in time and space;
2) none of the micro processes are themselves informative concerning the function that they will assume with respect to others, nor the global process of which it will be part.

This computational philosophy, very economic for the creation of simple models, can be used effectively to create any type of process or model that is inspired by complex processes. NC in fact deals with the construction of artificial models that do not simulate the complexity of Natural and/or Cultural Processes through rules, but rather, through commitments that, depending on the space and time through which the process takes form, autonomously

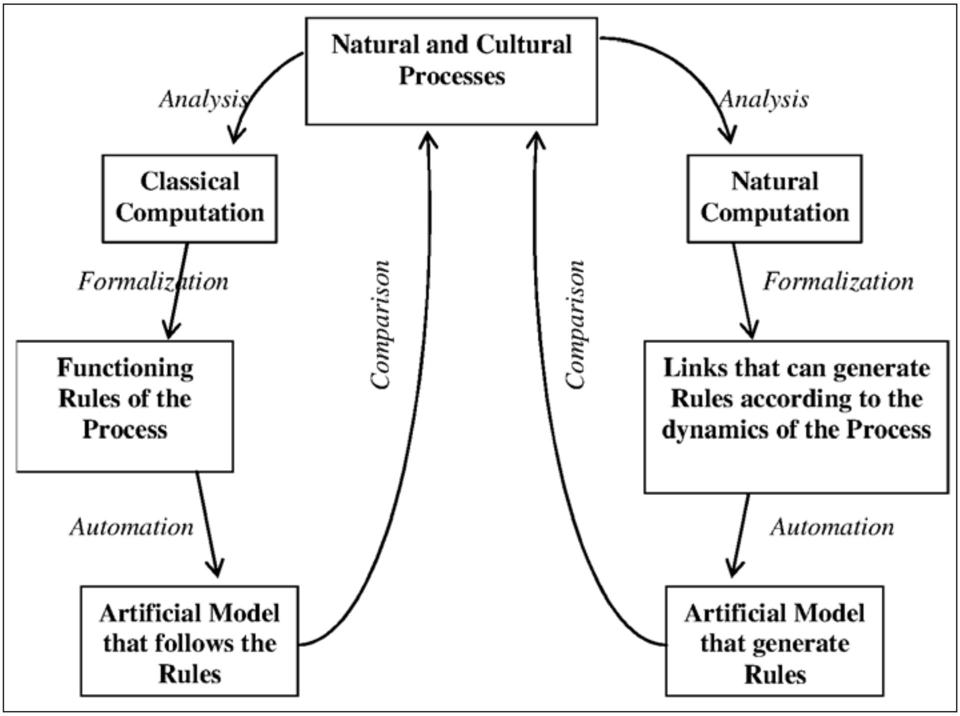


Fig. 3 – The diagram shows in more detail the formalization, automation and comparison between Natural and/or Cultural Processes and Automatic Artificial Models seen from two points of view (Classical Computation and NC). Each point of view can be seen as a cycle that can repeat itself several times. This allows one to deduce that the human scientific process characterizing both the cycles resembles more the NC than the Classical Computation one.

create a set of contingent and approximate rules. NC does not try to recreate Natural and/or Cultural Processes by analyzing the rules which make them function, and thus formalizing them into an artificial model.

On the contrary, NC tries to recreate Natural and/or Cultural Processes by constructing artificial models able to create local rules dynamically and therefore capable of change in accordance with the process itself. The links that enable NC models to generate rules dynamically are similar to the Kantian transcendental rules: these are rules that establish the conditions of possibility of other rules. In NC, dynamics such as learning to learn are implicit in the artificial models themselves, whilst in Classical Computation additional rules are required (Fig. 3). NC can be decomposed into the following:

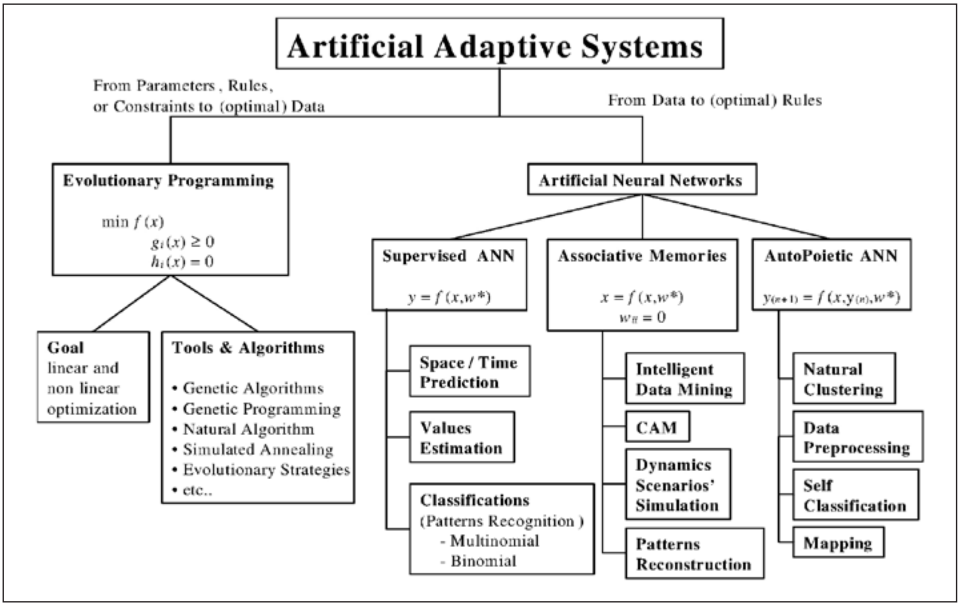


Fig. 4 – Artificial Adaptive Systems: general diagram.

– Descriptive Systems (DS): are derived from disciplines that have developed, whether or not intentionally, a formal algebra that has proved particularly effective in drawing up appropriate functioning links of artificial models generated within NC (for example: the Theory of the Dynamic Systems, the Theory of Autopoietic Systems, Fuzzy Logic, etc.).
– Generative Systems (GS): theories of NC that have explicitly provided a formal algebra aimed at generating artificial models of Natural and/or Cultural Processes through links that create dynamic rules in space and in time. In turn, Generative Systems can be broken down into:
– Physical Systems (PS): a grouping of those theories of NC whose generative algebra creates artificial models comparable to physical and/or cultural processes, only when the artificial model reaches given evolutionary stages (limit cycles type). Whilst not necessarily the route through which the links generate the model, it is itself a model of the original process. In brief, in these systems in which the generation time of the model is not necessarily an artificial model of the evolution of the process time (for example: Fractal Geometry, etc.).
– Artificial Adaptive Systems (AAS): theories of NC whose generative algebra creates artificial models of Natural and/or Cultural Processes, whose birth

process is itself an artificial model comparable to the birth of the original process. They are therefore theories assuming the emergence time in the model as a formal model of the process time itself.

In short: for these theories, each phase of artificial generation is a model comparable to a Natural and/or Cultural process. Artificial Adaptive Systems in turn comprise (Fig. 4):

– Learning Systems (Artificial Neural Networks – ANNs): these are algorithms for processing information that allow for the reconstruction, in a particularly effective way, of the approximate rules relating to a set of "explanatory" data concerning the considered problem (the Input), with a set of data (the Output) for which it is requested to make a correct forecast or reproduction in conditions of incomplete information.
– Evolutionary Systems (ES): the generation of adaptive systems changing their architecture and their functions over time in order to adapt to the environment into which they are integrated, or comply with the links and rules that define their environment and, therefore, the problem to be simulated. Basically, these are systems that are developed to find data and/or optimum rules within the statically and dynamically determined links and/or rules. The development of a genotype from a time ti to a time t (i+n) is a good example of the development over time of the architecture and functions of an adaptive system.

2. A brief introduction to Artificial Neural Networks

2.1 *Architecture*

ANNs are a family of methods inspired to the human brain learning capability.

ANNs are scientifically used in three different epistemological directions:

1) To understand the working of human brain, by simulation;
2) To optimize parallel computation research (human brain emulation);
3) To understand the transition from individual to collective behavior (Data Analysis, Data Mining and the research on Complex Systems are part of this point).

Currently ANNs comprise a range of very different models, but they all share the following characteristics:

1) The fundamental elements of each ANN are the Nodes, also known as Processing Elements (PE), and their Connections.
2) Each node in an ANN has its own Input, through which it receives communications from the other nodes or from the environment; and its own Output, through which it communicates with other nodes or with the en-

vironment. Finally it has a function, f(•), by which it transforms its global Input into Output.
3) Each Connection is characterized by the force with which the pair of nodes excites or inhibits each other: positive values indicate excitatory connections and negative ones indicate inhibitory connections.
4) Connections between nodes may change over time. This dynamic triggers a learning process throughout the entire ANN. The way (the law by which) the connections change in time is called the "Learning Equation".
5) The overall dynamic of an ANN is linked to time: in order for the connections of the ANN to properly change, the environment must act on the ANN several times.
6) When ANNs are used to process data, these latter are their environment. Thus, in order to process data, these latter data must be subjected to the ANN several times.
7) The overall dynamic of an ANN depends exclusively on the local interaction of its nodes. The final state of the ANN must, therefore, evolve spontaneously from the interaction of all of its components (nodes).
8) Communications between nodes in every ANN tend to occur in parallel. This parallelism may be synchronous or asynchronous and each ANN may emphasize it in a different way. However, an ANN must present some form of parallelism in the activity of its nodes.

From a theoretical viewpoint this parallelism does not depend on the hardware on which the ANNs are implemented. Every ANN must present the following architectural components:

1) Type and number of nodes and their corresponding properties;
2) Type and number of connections and their corresponding location;
3) Type of Signal Flow Strategy;
4) Type of Learning Strategy.

2.2 *The nodes*

There can be three types of ANN nodes, depending on the position they occupy within the ANN:

1) Input nodes: the nodes that (also) receive signals from the environment outside the ANN.
2) Output nodes: the nodes whose signal (also) acts on the environment outside the ANN.
3) Hidden nodes: the nodes that receive signals only from other nodes in the ANN and send their signal only to other nodes in the ANN.

The number of Input nodes depends on the way the ANN is intended to read the environment. The Input nodes are the ANN's sensors. When the

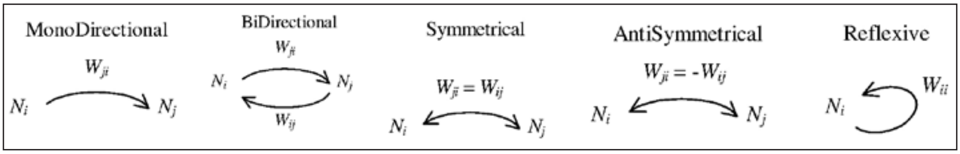


Fig. 5 – Types of possible connections.

ANN's environment consists of data the ANN should process, the Input node corresponds to a sort of data variable. The number of Output nodes depends on the way one wants the ANN to act on the environment. The Output nodes are the effectors of the ANN. When the ANN's environment consists of data to process, the Output nodes represent the variables sought or the results of the processing that occurs within the ANN. The number of hidden nodes depends on the complexity of the function one intends to map between the Input nodes and the Output nodes. The nodes of each ANN may be grouped into classes of nodes sharing the same properties. Normally these classes are called layers. Various types can be distinguished:

1) Monolayer ANNs: all nodes of the ANN have the same properties.
2) Multilayer ANNs: the ANN nodes are grouped in functional classes; for example, nodes that (a) share the same signal transfer functions or (b) receive the signal only from nodes of other layers and send them only to new layers.
3) Nodes Sensitive ANNs: each node is specific to the position it occupies within the ANN; e.g. the nodes closest together communicate more intensely than they do with those further away.

2.3 *The connections*

There may be various types of connections: Mono-Directional, Bi-directional, Symmetrical, Anti-Symmetrical and Reflexive (Fig. 5). The number of connections is proportional to the memory capabilities of the ANN. Positioning the connections may be useful as methodological preprocessing for the problem to be solved, but it is not necessary. An ANN in which the connections between nodes or between layers are not all enabled is called an ANN with Dedicated Connections; otherwise it is known as a maximum gradient ANN. In each ANN the connections may be:

1) Adaptive: they change depending on the learning equation.
2) Fixed: they remain at fixed values throughout the learning process.
3) Variable: they change deterministically as other connections change.

2.4 *The signal flow*

In every ANN the signal may proceed in a direct fashion (from Input to Output) or in a complex fashion. Thus we have two types of Flow Strategy:

1) Feed forward ANN: the signal proceeds from the Input to the Output of the ANN passing all nodes only once.
2) ANN with Feedback: the signal proceeds with specific feedbacks, determined beforehand, or depending on the presence of particular conditions.

The ANNs with Feedback are also known as Recurrent ANNs, and are the most plausible from a biological point of view. They are often used to process timing signals and they are the most complex to deal with mathematically. In an industrial context, therefore, they are often used with feedback conditions determined *a priori* (in order to ensure stability).

3. Learning in the Artificial Neural Network

Every ANN can learn, over some period of time, the properties of the environment in which it is immersed or the characteristics of the data which it presents. This is accomplished in basically one of two ways (or mixture of both):

1) By reconstructing approximately the probability density function of the data received from the environment, compared with preset constraints.
2) By reconstructing approximately the parameters which solve the equation relating the Input data to the Output data, compared with preset constraints.

The first method is known in the context of ANNs as Vector Quantization; the second method is Gradient Descent. The Vector Quantization method articulates the Input and Output variables in hyperspheres of a defined range. The Gradient Descent method articulates the Input and Output variables in hyperplanes. The difference between these two methods becomes evident in the case of a feed forward ANN with at least one hidden unit layer. With Vector Quantization the hidden units encode locally the more relevant traits of the Input vector. At the end of the learning process, each hidden unit will be a Prototype representing one or more relevant traits of the Input vector in definitive and exclusive form. With Gradient Descent, the hidden units encode in a distributed manner the most relevant characteristics of the Input vector. At the end of the learning process, each hidden unit will tend to represent the relevant traits of the Input in a fuzzy and non-exclusive fashion. Summing up, the Vector Quantization develops a local learning, and the Gradient Descent develops a distributed or vectorial learning. Considerable differences exist between the two approaches:

1) Distributed learning is computationally more efficient than local learning. It may also be more biologically plausible (not always nor in every case).
2) When the function that connects Input to Output is nonlinear, distributed learning may “jam” on local minimums due to the use of the Gradient Descent technique.
3) Local learning is often quicker than distributed learning.
4) The regionalization of Input on Output is more sharply defined when using Vector Quantization than when using Gradient Descent.
5) When interrogating an ANN trained with Vector Quantization, the ANN responses cannot be different from those given during learning; in the case of an ANN trained with Gradient Descent the responses may be different from those obtained during the learning phase.
6) This feature is so important that families of ANNs treating the signal in 2 steps have been designed: first with the Quantization method and then with the Gradient method.
7) Local learning helps the researcher to understand how the ANN has interpreted and solved the problem; distributed learning makes this task more complicated (though not impossible).
8) Local learning is a competitive type; distributed learning presents aspects of both competitive and cooperative behavior between the nodes.

4. Artificial Neural Network typology

Traditionally ANNs are divided into two families: Supervised ANNs and Unsupervised ANNs. But from a theoretical point of view this distinction could be superficial. An interesting viewpoint on this theoretical debate can be gained by noting that, from the point of view of the energy function that is being calculated by an unsupervised vs. a supervised ANN, it is easy to subsume both approaches into a common framework. The energy function for a supervised ANN can be written as its Mean Square Error:

$$MSE = \frac{1}{2}\sum_{n}^{K}\sum_{i}^{N}\left(t_{p,i} - u_{p,i}\right)^2 \tag{1}$$

Whereas, traditionally, the energy minimization function in an unsupervised auto-associative neural network is represented by the following equation:

$$En = \frac{1}{2}\sum_{p}^{K}\sum_{i}^{N}\sum_{j}^{n}\left(u_{p,i} \cdot u_{p,j} \cdot w_{i,j}\right) \tag{2}$$

where $w_{i,j}$ = trained weights from Input *j* to Input *i*.

But if we assume that equation (1) represents the mean error of a linear perceptron, then we can develop equation (1) as follows:

$$MSE = \frac{1}{2}\sum_{p}^{K}\sum_{i}^{N}\left(t_{p,i} - u_{p,i}\right)^2 = \frac{1}{2}\cdot\sum_{p}^{K}\sum_{i}^{N}\left(t_{p,i} - \sum\nolimits_{j}^{N} u_{p,i}\cdot w_{i,j}\right)^2 =$$
$$\frac{1}{2}\sum_{p}^{K}\sum_{i}^{N}\left(t_{p,i}^2 - 2\cdot t_{p,i}\cdot\sum_{j}^{N} u_{p,j}\cdot w_{i,j} + \left(\sum_{j}^{N} u_{p,i}\cdot w_{i,j}\right)^2\right) \tag{3}$$

Setting all targets to 0, as in the case of unsupervised neural networks, we have:

$$MSE = \frac{1}{2}\sum_{p}^{K}\sum_{i}^{N}\left(\sum_{j}^{N} u_{p,j}\cdot w_{i,j}\right)^2 =$$
$$\frac{1}{2}\sum_{p}^{K}\sum_{i}^{N}\left(\sum_{j}^{N} u_{p,j}\cdot w_{i,j}\right)\left(\sum_{j}^{N} u_{p,j}\cdot w_{i,j}\right) = \tag{4}$$
$$\frac{1}{2}\sum_{p}^{K}\sum_{i}^{N} u_{p,i}\left(\sum_{j}^{N} u_{p,j}\cdot w_{i,j}\right)$$

At this point it is easy to derive:

$$MSE = \frac{1}{2}\sum_{p}^{K}\sum_{i}^{N}\sum_{j}^{N} u_{p,i}\cdot u_{p,j}\cdot w_{i,j} \tag{5}$$

and equation (5) is the energy function for an unsupervised ANN (see equation (2).

Therefore:

$$En = MSE\ when\ (target = 0) \tag{6}$$

We can thus in principle regard unsupervised ANN learning as a conceptually more economical approach than supervised learning in that it entails doing away with some free parameters, namely, targets. Or, on the other hand, we can make a case for supervised learning, i.e. for the inclusion of the extra free parameters, as a way to focus the learning model upon a more clear-cut task. Adopting this point of view ANNs can be classified into three sub families:

1) Supervised ANNs;
2) Unsupervised Auto Associative Memories;
3) Unsupervised Autopoietic ANNs.

Furthermore, a unique pseudo code can be used as general framework to build any kind of ANN (Supervised and Unsupervised):

```
1. Design of the Architecture of the Network
2. Initialization of Weights
3. Do Epochs
        {
                do Cycles
                {
                a. Presentation of one Pattern as Input Vector
                b. Signal Transfer up to the Output layer
                c. Error Computation for each Node and Weight
                d. Weights and/or Nodes updating
                e. Possible Recurrence
                } Until (all Patterns are presented)
        } Until (Cost Function is Optimized)
```

At this point we can describe from a didactic standpoint three families of different problem and consequently the three more famous families of ANNs.

4.1 *Supervised ANNs*

The first type of problem with which an ANN can deal is expressed as follows: given N variables, about which it is easy to gather data, and M variables, which differ from the first and about which it is difficult and costly to gather data, assess whether it is possible to predict the values of the M variables on the basis of the N variables. This family of ANNs is named Supervised ANNs (SV) and their prototypical equation is:

$$y = f(x, w^*) \tag{7}$$

where y is the vector of the M variables to predict and/or to recognize (target), x is the vector of N variables working as networks Inputs, w is the set of parameters to approximate and f ( ) is a non-linear and composed function to model. When the M variables occur in time subsequent to the N variables, the problem is described as a prediction problem; when the M variables depend on some sort of typology, the problem is described as one of recognition and/or classification (this is also sometimes referred to as the proscription problem).

Conceptually it is the same kind of problem: using values for some known variables to predict the values of other unknown variables. In order to correctly apply an ANN to this type of problem we need to run a validation protocol. We must start with a good sample of cases, in each of which the N variables (known) and the M variables (to be discovered) are both known and reliable. The sample of complete data is needed in order to:

1) train the ANN, and
2) assess its predictive performance.

The validation protocol uses part of the sample to train the ANN (Training Set), whilst the remaining cases are used to assess the predictive capability of the ANN (Testing Set or Validation Set). In this way we are able to test the reliability of the ANN in tackling the problem before putting it into operation. Now we provide some example of Supervised ANNs.

4.2 *The Multi-Layer Perceptron*

Back Propagation (BP for short) refers to a broad family of Multi-Layer Perceptron, whose architecture consists of different interconnected layers [1-4]. The BP ANNs represents a kind of supervised ANN, whose learning's algorithm is based on the Deepest-Descent technique. If provided with an appropriate number of Hidden units, they will also be able to minimize the error of nonlinear functions of high complexity (Fig. 6).

Theoretically, a BP provided with a simple layer of Hidden units is sufficient to map any function $y = f(x)$. Practically, it is often necessary to provide these ANNs with at least 2 layers of Hidden units, when the function to compute is particularly complex, or when the chosen data, in order to train the BP, are not particularly reliable, and a level filter is necessary on the features of Input. The BP are networks, whose learning function tends to "distribute itself" on the connections, just for the specific correction algorithm of the weights that is utilized. This means that, in the case of BP, provided with at least one layer of Hidden units, these units tend to distribute among themselves the codification of each feature of the Input vector.

This makes the learning more compact and efficient, but it is more complex to know the "reasoning" which brings a BP, in the testing process, to answer in a certain way. In brief, it is difficult to explain the implicit knowledge acquired by these ANNs in the training process.

A second theoretical and operative difficulty raised by BP concerns the minimum number of Hidden units that are necessary for these ANNs in order to compute a function. In fact, it is known that if the function is not linear, at least one layer of Hidden units will be necessary. But, at the moment, the exact minimum number of Hidden units needed to compute a non-linear function is unknown. In these cases, we base our work on experience and on some heuristics.

Experience advises us to use a minimum number of Hidden units in a first time training of an ANN. If the training succeeds, an analysis of the

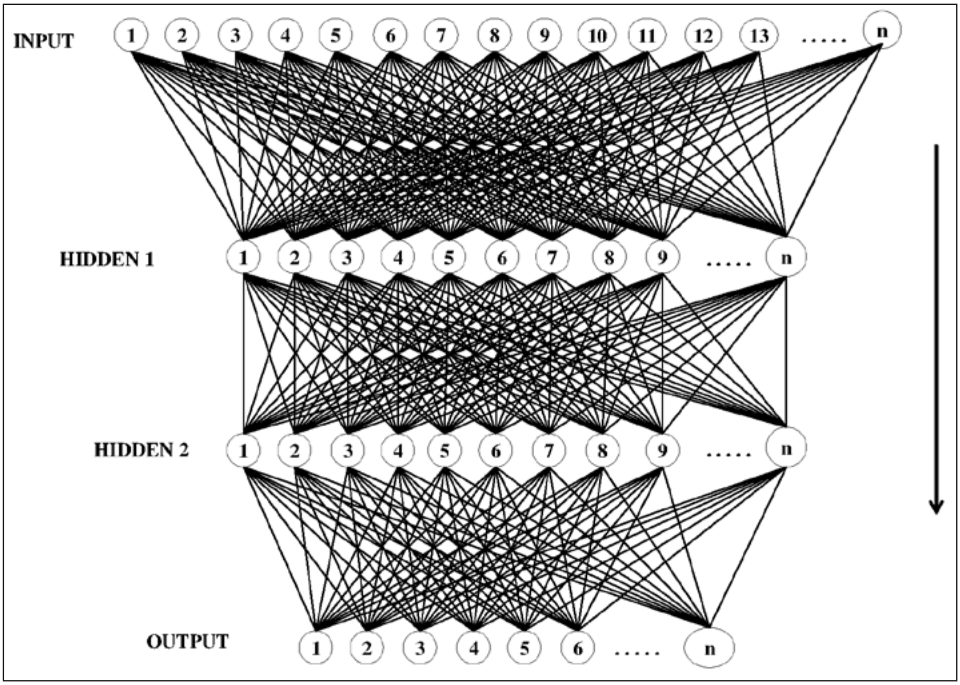


Fig. 6 – Example of Multi-Layer Perceptron.

sensitivity will normally allow us to understand the singularity number that each Input node determines on the Output, and, consequently, it will be able to deduce the degree of freedom needed by the ANN to resolve the equation, and then to express these latter under the form of Hidden units. This procedure is not guaranteed; during the training process the BP can become trapped in local's minima.

This is because of the relation between the morphology complexity of the hyper surface that characterizes the function and the weights' values, randomly set and placed before the training.

The dilemma of BP is that for a prior, unknown minimum number of Hidden units useful to compute a function, if too many are created, the BP can create during some forms of training a condition of over fitting, which causes a worsening of its generalization capacities in the testing process. If not too many are created, the BP can have difficulty learning either because the function is too complex, or because the BP randomly falls into a local minimum. The BP's family includes both Feed Forward ANN and Feedback ANN, also known as Recurrent Networks (Chauvin, Rumelhart 1995).

4.3 *The Conic Net*

The Conic Net is a supervised ANN, designed by P.M. Buscema in 2013 and never published before. The architecture is similar to that of a Multilayer Perceptron, but its hidden layer is completely different. Each traditional node of the classic Hidden layer in the case of the Conic Net (CN) is decomposed in 3 sub nodes connected by 6 weights, according to Fig. 7a. This topology aims to transform each complex hidden node into a quadratics equation, whose parameters have to be learned during the training phase (Fig. 7b).

The singularity of Conic Net in relation to the other and more classic MLP is its complex hidden layer structure: two sub nodes receiving their weights vectors independently from the same Input vector and one sub node working as Output node, receiving the 6 parameters from the quadratics equation, including the two previous sub nodes as X and Y of the conic function. Further, it is interesting to note that the two X and Y sub nodes modify their incoming weights each one according to two different and independent learning laws: the gradient descent (the X sub node) and the quantization algorithm (the Y sub node).

The following equations show how the signals flow from Input layer to Output layer in the Conic Net:

$$Net_i = \sum_{j}^{N} u_j \cdot w(x)_{i,j} + \theta_i \tag{8}$$

$$Qx_i = \frac{1}{1 + e^{-Net_i}} \tag{9}$$

$$D_i = \sum_{j}^{N} (N \cdot (2 \cdot u_i - 1) - w(y)_{i,j})^2 \tag{10}$$

$$Qy_i = \left(1 - \frac{\sqrt{D_i}}{N}\right) \cdot Exp\left(-\frac{D_i}{N}\right) \tag{11}$$

$$C_i = aQ \cdot x^2\ 2bQxQx + cQ \cdot y^2 + 2dQx + 2eQy + f \tag{12}$$

$$Qz_i = \frac{1}{1 + e^{-C_i}} \tag{13}$$

where:

u = Input Vector
N = Number of Inputs
Qx = Output of the X sub node of the CN hidden layer
Qy = Output of the Y sub node of the CN hidden layer

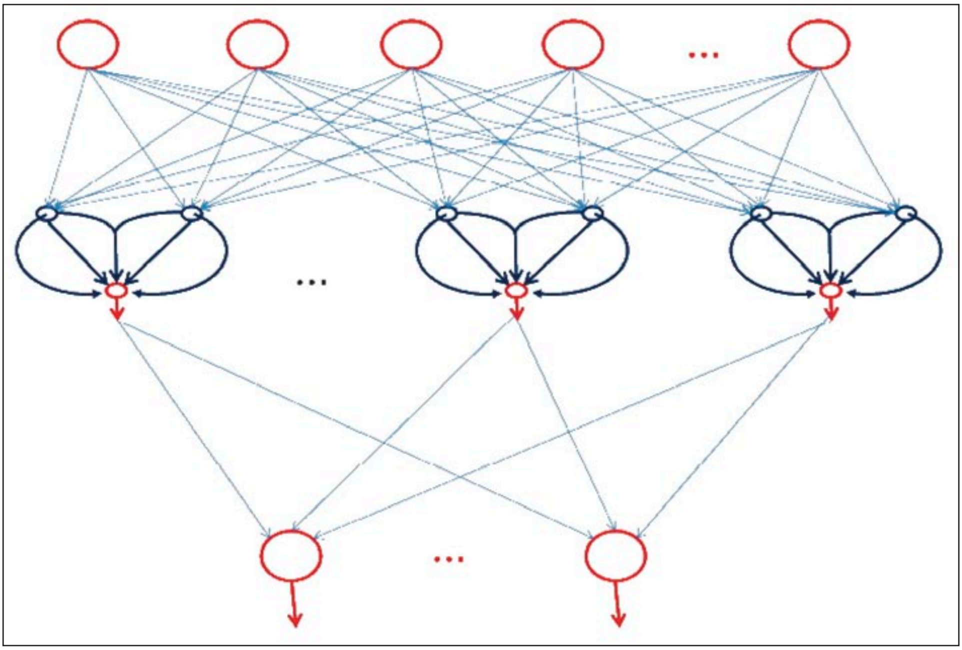


Fig. 7a – Topology of Conic Net (in blue the Hidden layer).

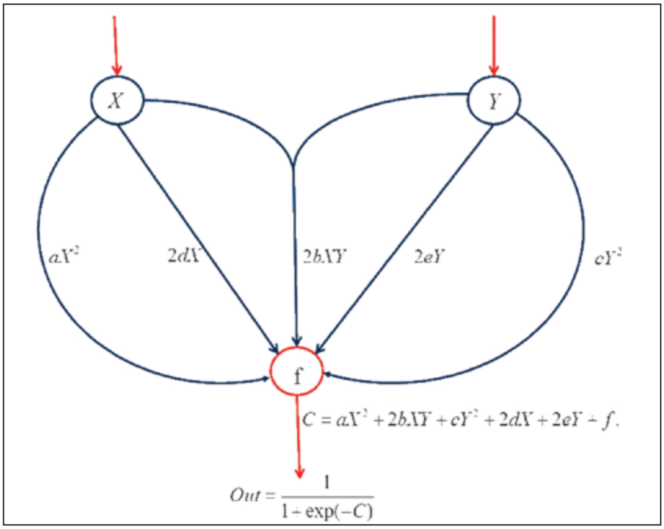


Fig. 7b – Close up of one macro hidden node of a Conic Net.

C = Output of the third sub node of the CN hidden layer

The following equations show how we calculate the local error in CN:

$$\delta_i^{[n]} = \sum_{j=1}^{N} \delta_j^{[n+1]} \cdot w_{ji}^{[n+1]} \tag{14}$$

$$\Delta w(x)_{i,j}^{[n]} = \delta_i^{[n]} \cdot f'(Qx_i) \cdot u_j^{[n-1]} \cdot \varepsilon \tag{15}$$

$$\Delta w(y)_{i,j}^{[n]} = \delta_i^{[n]} \cdot (Qy_i) \cdot \left(N \cdot (2 \cdot u_j^{[n-1]} - 1 - w(Qy)_{i,j}\right) \cdot \varepsilon \tag{16}$$

$$\Delta w_a = \delta_i^{[n]} \cdot Qx_i^2 \cdot \varepsilon \tag{17}$$

$$\Delta w_b = \delta_i^{[n]} \cdot 2 \cdot Qx_i \cdot Qx_y \cdot \varepsilon \tag{18}$$

$$\Delta w_c = \delta_i^{[n]} \cdot 2 \cdot Qy^2 \cdot \varepsilon \tag{19}$$

$$\Delta w_d = \delta_i^{[n]} \cdot 2 \cdot Qx_i \cdot \varepsilon \tag{20}$$

$$\Delta w_e = \delta_i^{[n]} \cdot 2 \cdot Qx_y \cdot \varepsilon \tag{21}$$

$$\Delta w_f = \delta_i^{[n]} \cdot \varepsilon \tag{22}$$

where:

$\delta_j^{[n+1]}$ = error of the next layer calculated BP delta rule

$w_{ji}^{[n+1]}$ = the weights matrix of the next layer

And, finally, the equations by means we correct the Input weights and the quadratics weights (parameters) of the CN:

$$w(x)_{i,j}(t+1) = w(x)_{i,j}(t) \cdot \Delta w(x)_{i,j}^{[n]} \tag{23}$$

$$w(y)_{i,j}(t+1) = w(y)_{i,j}(t) \cdot \Delta w(y)_{i,j}^{[n]} \tag{24}$$

$$w_a(t+1) = w_a(t) + \ w\Delta_{\square} \tag{25}$$

$$w_b(t+1) = w_b(t) + \ w\Delta_b \tag{26}$$

$$w_c(t+1) = w_c(t) + \ w\Delta_c \tag{27}$$

$$w_d(t+1) = w_d(t) + \ w\Delta_d \tag{28}$$

$$w_e(t+1) = w_e(t) + w\Delta_e \tag{29}$$

$$w_f(t+1) = w_f(t) + w\Delta_f \tag{30}$$

The CN presents also many suitable features that in this paper are not pertinent to describe into details.

4.4 *The Supervised Contractive Map*

The Supervised Contractive Map (SVCM for short) was designed by M. Buscema in 1999 (Buscema, Benzi 2011). This ANN calculates two net Inputs for each node: a classic weighted Input (see Equation 31) and a contractive Input (see Equation 32). This second net Input tends to decay or to increase when the positive or negative value of the weight (w) becomes close to a specific constant (C). Equation 33 activates each node according to a sine function of the two net Inputs (the contractive Input works as a harmonic modulation of the weighted Input). The vantages and the disadvantages of sine transfer function to work properly into the topology of Multilayer Perceptron were already analyzed in the scientific literature (Le Cun *et al.* 1991).

$$CNet_i^{[l]} = \sum_j^{C^{[l-1]}} u_j^{[l-1]} \cdot \left(1 - \frac{w_{i,j}^{[l]}}{C^{[l-1]}}\right) \tag{31}$$

$$INet_i^{[l]} = \sum_j^{C^{[l-1]}} u_j^{[l-1]} \cdot w_{i,j}^{[l]} \tag{32}$$

$$u_i^{[l]} = sin\left(INet_i^{[l]} \cdot \left(1 - \frac{\sin(CNet_i^{[l]})}{C^{[l-1]}}\right)\right) \tag{33}$$

Equation 34 shows a typical error calculation using the distance between the desiderate Output and the estimated Output, times the first derivative of sine transfer function. Equation 35 works in the same way of Equation 34, but using the chain rule to calculate the local error of each hidden unit. Equation 36 updates the weight matrices, using typical back error propagation, with a contractive factor useful to limit an extreme growing of each weight value.

$$\delta_i^{[out]} = (t_i - u_i^{out}) \cdot \cos\left(INet_i^{[out]} \cdot \left(1 - \frac{\sin\left(CNet_i^{[out]}\right)}{C^{[out-1]}}\right)\right) \tag{34}$$

$$\delta_i^{[hid]} = \sum_{k}^{Num[hid+1]} (\delta_k^{[k+1]} \cdot w_{k,i}^{[hid+1]}) \cdot \cos\left(INet_i^{[hid]} \cdot \left(1 - \frac{\sin\left(CNet_i^{[hid]}\right)}{C^{[hid-1]}} \right) \right) \tag{35}$$

$$\Delta w_{i,j}^{[l]} = LCoef \cdot \delta_i^{[l]} \cdot u_j^{[l-1]} \cdot \left(1 - \frac{w_{i,j}^{[l]}}{C^{[l-1]}} \right) \tag{36}$$

where:

[l] = number or name of the ANN layer;

$u_j^{[l]}$ = values of the all i-th nodes of the l-th layer;

$w_{i,j}^{[l]:}$ = weight matrix connecting the layer [l-1] to the layer [l];

$C^{[l]}$: number of nodes of the l-th layer;

t_i: = value of the i-th of the dependent variable;

LCoef = ANN learning rate.

The SVCM is been already tested for the approximation of highly non-linear and complex interpolation with excellent results (Buscema, Benzi 2011).

4.5 *Dynamic Associative Memories*

The second type of problem that an ANN raises can be expressed as follows: given N variables defining a dataset, find out its optimal connections matrix able to define each variable in terms of the others and consequently to approximate the hyper-surface on which each data-point is located.

This second sub-family of ANNs is named Dynamic Associative Memories (DAM). The specificity of these ANNs is incomplete pattern reconstruction, dynamic scenario simulation and possible situations prototyping. Their representative equation is:

$$x^{[n+1]} = f(x^n, w^*) \tag{37}$$

where x[n] is the N variables evolving in the ANNs internal time, w* is the connection matrix approximating the parameters of the hyper-surface representing the dataset, and f() is some suitable non-linear and eventually composed function governing the process. DAM ANNs after the training phase need to be submitted to a validation protocol named “Data Reconstruction Blind Test”. In this test the capability of a DAM ANN to rebuild complete data from uncompleted ones is evaluated from a quantitative point of view. Now we describe briefly some type of Auto-Associative Memory ANN.

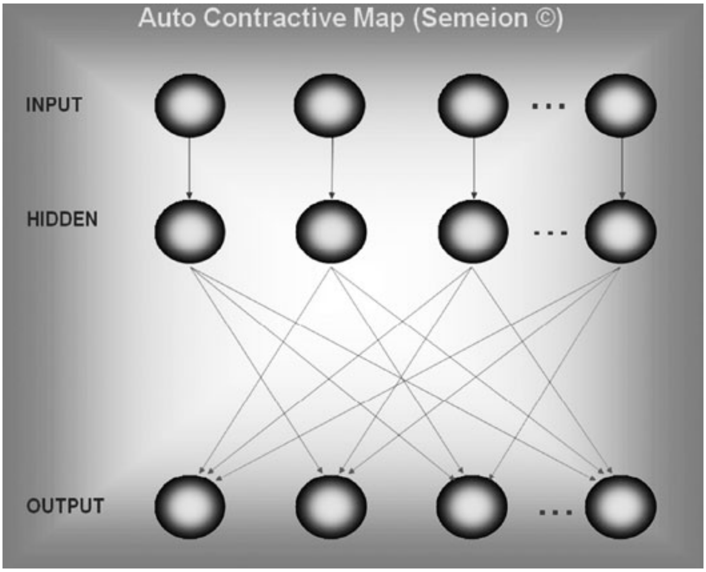


Fig. 8 – AutoContractive Map.

4.6 *AutoContractive Map*

The AutoContractive Map neural network (Auto-CM for short) was designed by P. M. Buscema in 1999 and its learning law was improved up to 2013. Auto-CM was explained in different papers and it was applied in many fields with promising results (Buscema 2007a, 2007b; Buscema *et al.* 2008a, 2008b, 2010; Buscema, Sacco 2010; Licastro *et al.* 2010; Grossi *et al.* 2011). The software implementing Auto-CM is developed by Semeion Research Center in Rome and it is available free for academic applications. Auto-CM has an architecture based on three layers of nodes: an Input layer that captures the signal from the environment, a hidden layer which modulates the signal within the network, and an Output layer which returns a response to the environment on the basis of the processing that occurred. The three layers have the same number N of nodes.

The connections between the Input layer and the hidden one are mono-dedicated, whereas those between this hidden layer and the Output layer are completely connected. Each connection is assigned a weight: v_i for connections between the i^{th} Input node and the corresponding hidden node, $w_{i,j}$ for those between the generic j^{th} node of the hidden layer and the i^{th} node of the Output layer (Fig. 8). For the training, datasets are scaled between zero and one and all weights are initialized beforehand to the same positive value close to zero.

Symbol	*Meaning*
x_i^p	*i^{th} input node of the p^{th} pattern*
$h_i^p(n)$	*i^{th} hidden node of the p^{th} pattern during the n^{th} time*
$y_i^p(n)$	*i^{th} node in the output of the p^{th} pattern during the n^{th} epoch*
$v_i(n)$	*weight of the connection between the i^{th} input node and in the i^{th} hidden node during the n^{th} epoch*
$w_{i,j}(n)$	*weight of the connection between the j^{th} hidden node and the i^{th} output node during the n^{th} epoch*
N	*the number of nodes per layer*
M	*the number of patterns*
α	*constant learning rate*
C	*constant greater than one, typically* $C = \sqrt{N}$

Tab. 1 – Notation for Auto-CM Neural Network.

Then the network must undergo a series of epochs. In each of them, all the Input patterns must be presented one after another to the network, and a calculation made for the appropriate equations with the corresponding Output value and a measure of error with respect to the desired value. In accordance with the principle of batch update, the corrections accumulated for an epoch must be applied at the end. The equations of training of the network make reference to the quantities shown below (Tab. 1).

At the n^{th} epoch of training, out of each Input pattern a value is calculated for the hidden layer, through a contraction, that reduces the Input value in proportion to the mono-dedicated weight.

$$h_i^{[p]}(n) = x_i^{[p]} \cdot (1 - \frac{v_i(n)}{C}) \tag{38}$$

The algorithm then calculates the value on the Output layer through a "double conceptual passage". For each Output node, an initial operation saves the net Input calculation, that is to say, the reduction (contraction) of all the hidden nodes through the weights between the hidden layer and Output layer (Equation 39).

$$Net_i^{[p]}(n) = \sum_{j=1}^{N} h_i^{[p]}(n) \cdot (1 - \frac{v_i(n)}{C}) \tag{39}$$

A second operation calculates the Output value by further contracting the corresponding value of the hidden node thorough the previously calculated net Input for the Output node:

$$y_i^{[p]}(n) = h_i^{[p]}(n) \cdot (1 - \frac{Net_i^{[p]}(n)}{C} \tag{40}$$

During the training that occurs in every epoch, in addition to the calculation of the Output values (40), for each pattern presented in Input the algorithm calculates the correction quantity of the weights, summed and applied at the end of the epoch. For the N-mono dedicated layers between the Input and hidden layers, the algorithm considers the contraction, based on the weight being examined, of the difference between the values of the corresponding Input and hidden nodes, further modulated for the Input node itself.

$$\Delta v_i(n) = \sum_{p=1}^{M} (x_i^{[p]} - h_i^{[p]}(n)) \cdot (1 - \frac{v_i(n)}{C}) \tag{41}$$

$$v_i(n+1) = v_i(n) + \alpha \cdot \Delta v_i(n) \tag{42}$$

Similarly, for N2 weights between the hidden and Output layers the algorithm calculates the contraction, based on the weight being considered, between the corresponding hidden and Output nodes.

$$\Delta w_i(n) = \sum_{p=1}^{M} (h_i^{[p]} - y_i^{[p]}(n)) \cdot (1 - \frac{w_{i,j}(n)}{C}) \cdot h_i^{[p]}(n) \tag{43}$$

$$w_{i,j}(n+1) = w_{i,j}(n) + \alpha \cdot \Delta w_{i,j}(n) \tag{44}$$

The equations immediately illustrate how the contractions establish a relationship of order between the layers:

$$x_i^{[p]} \geq h_i^{[p]}(n) \geq y_i^{[p]}(n) \tag{45}$$

As we can easily observe during the training, the mono-dedicated weights vi grow monotonically, and with different speeds asymptotically towards the constant C:

$$\lim_{x \to \infty} \Delta w_i(n) = 0 \tag{46}$$

$$\lim_{x \to \infty} v_i(n) = C \tag{47}$$

just like the values of hidden nodes tend to cancel themselves out:

$$\lim_{x \to \infty} h_i^{[p]}(n) = 0 \tag{48}$$

along with those of the Output units:

$$\lim_{x \to \infty} y_i^{[p]}(n) = 0 \tag{49}$$

while the corrections of the full set of weights diminish:

$$\lim_{x \to \infty} \Delta w_{i,j}(n) = 0 \tag{50}$$

The process of cancelling the above quantity occurs with speed modulated by the Input patterns and leaves its specific sign in the matrix between the hidden and the Output layer.

4.7 *Autopoietic ANNs*

The third type of ANNs can be described as follows: given N variables defining M records in a dataset, evaluate how these variables are distributed and how these records are naturally clustered in a small projection space K (K<<N) according to their most important relationships. These ANNs are named Autopoietic ANNs. Their specificity is the nonlinear extraction of the similarities among records in a database, using all the variables at the same time.

One important feature of these ANNs is also the possibility that some of them have to visualize in a 2 or 3 dimensional map the geographical similarities among records and among variables. The prototypical equation of the Autopoietic ANNs is:

$$y^{[n+1]} = f(y^{[n]}, x, w^*) \tag{51}$$

where y is the projection result along the time, x is the Input vector (independent variables) and w is the set of parameters (codebooks) to be approximated. In Autopoietic ANNs, the codebooks (w) after the training phase represent an interesting case of cognitive abstraction: in each codebook the ANN tends to develop its abstract cognitive representation of some of the data which it learnt. Self-Organizing Map (SOM) is a known example of Autopoietic ANN.

4.8 *Self-Organizing Map (SOM)*

The Self-Organizing Map (SOM) is a neural network attributed to Teuvo Kohonen (1982, 1984, 1990, 1995), who developed it between 1979 and 1982. It is an unsupervised type of network which offers a classification of the Input vectors creating a prototype of the classes and a projection of the proto-

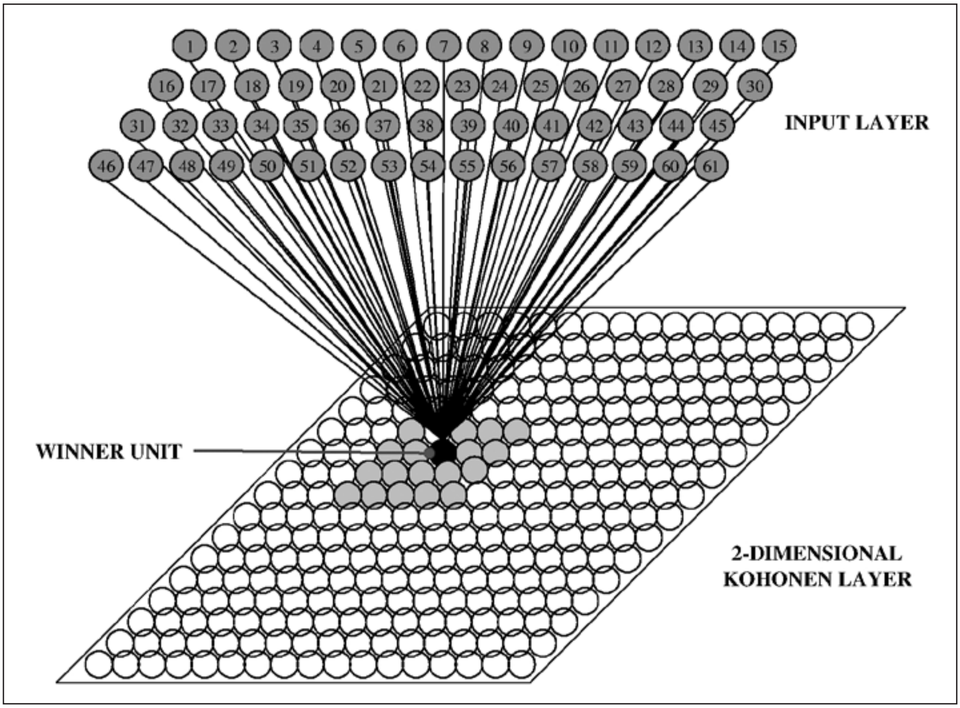


Fig. 9 – Example of Unsupervised ANN for natural clustering – Self-Organizing Map.

types on a two-dimensional map (but n-dimensional maps are also possible) able to record the relative proximity (or neighborhood) between the classes. Therefore, the network offers important synthetic information on the Input:

1) It operates a classification of the Input vectors on the basis of their vector similarity and assigns them to a class;
2) It creates a prototypical model of the classes with the same cardinality (number of variables) as the Input vector;
3) It provides a measurement, expressed as a numerical value, of the distance/proximity of the various classes;
d. It creates a relational map of the various classes, placing each class on the map itself;
4) It provides a measurement of the distance/proximity existing between the Input vectors from the class they belong to and between the Input vectors and other classes.

The relative simplicity of the network architecture allowed its dissemination in terms of how successfully its implementation could be replicated (Fig.

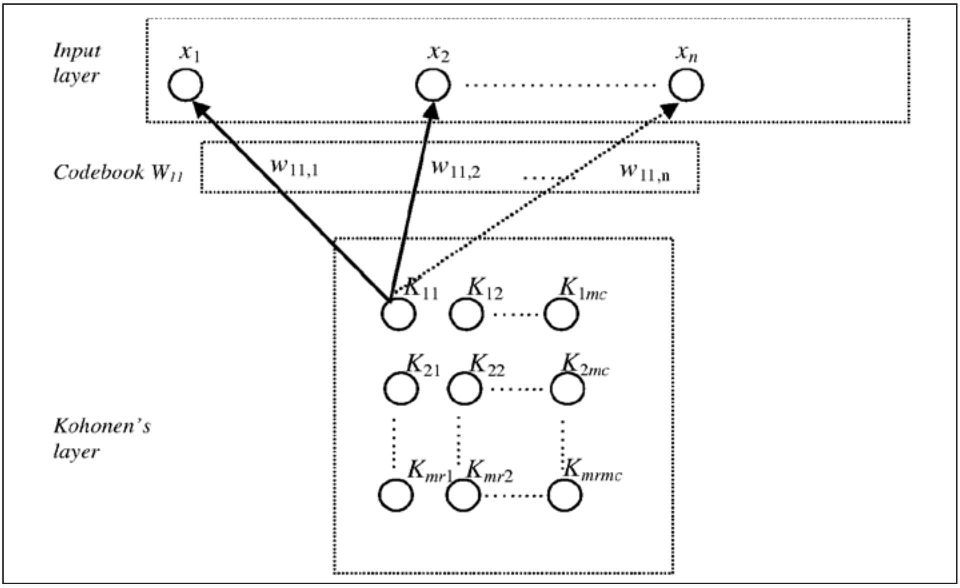


Fig. 10 – SOM with n-nodes of Input, with (mrmc) units of Kohonen's layer. This architecture allows the Inputs to be classified into m2 classes, each being a subclass represented by a codebook.

9). A typical SOM network is made up of 2 layers of units: a one-dimensional Input (n-cardinality vector) and a two-dimensional Output layer (lines (r) × columns (c)), also known as Kohonen's map (M matrix of mr x mc dimensions). A matrix of the weights records the relation between each unit of the Output layer and each unit of the Input layer (W matrix of (mr × mc × n) dimensions). The weight vector connecting each Output unit to an Input unit is called a "code-book" (vector wrc of n-cardinality) (Fig. 10).

Within the SOM network each Output unit can be interpreted as a class whose codebook represents the prototype. The SOM algorithm is based on a competitive algorithm founded on the vector quantification principle: at each cycle of life in the network, the unit from Kohonen's layer whose codebook is most similar to the Input wins. This unit is given the name of Winner Unit (WU). Consequently, the WU codebook is modified to get it even closer to the Input. The codebooks belonging to the units that are physically near the WU (which are part of the neighborhood) are also put closer to the Input of a given delta.

The algorithm calculates a first stage during which the parameters of neighborhood and corrections of weights are set and the codebook initialization is carried out; this stage is followed by the cyclic stage of codebook adjustment. In this stage the codebooks are modified for the network to classify the Input records. In short, the SOM algorithm is organized as follows:

Initialization stage:

1) Layering of the Input vectors;
2) Definition of the dimensions (rows x columns) of the matrix which, in its turn, determines the number of classes and therefore of prototypes (codebook);
3)Initialization of the codebooks: the values of the vectors of each codebook are random;
4) Definition of the function (Gaussian, Mexican hat, etc.) and of the parameters regulating the neighborhood of the Winner Unit and of the weight correction delta.

Cyclic calibration stage:

1) Presentation of the Input vectors (pattern) in a random and cyclic way.
2) Calculation of the d-activation of the *K* units of Kohonen's layer: the activation is calculated as vector distance between the Input vector X and the weight vector *Wj* (mj codebook) which links the *K* unit to the Input nodes.

The classic way to calculate the Euclidean distance between the vectors is:

$$d_j = \|X - W_j\| = \sqrt{\sum_{i=1}^{N} (x_i - w_{i,j)}^{\ 2}} \tag{52}$$

3) Determination of the winning unit WU: the node of the K layer whose activation is less:

$$WU = d_w = \min_{j \in [1,M]} \left\{ d_j \|X - W_j\| = \sqrt{\sum_{i=1}^{N} (x_i - w_{i,j)}^{\ 2}} \right\} \tag{53}$$

4) Correction of the codebook (matrix of the W_{ij} weights) of the winning unit and the units adjacent to the winning unit in relation to the function set to determine the level of weight correction according to the Input and the proximity to the *WU*.
5) Updating of the factors determining the proximity and layering of the delta correction of the codebooks.

The distinctive characteristic of the SOM is mainly related to the updating of the weights, carried out not only on those related to the WU but also, according to the chosen function, on the weights be-longing to the units which are physically close to it.

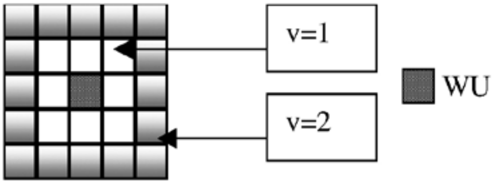
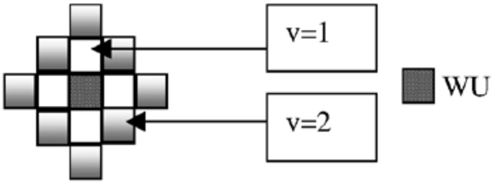
Square	Shape of the neighbourhood of the output matrix units 
Rhomb	Shape of the neighbourhood of the output matrix units 

Fig. 11 – Topology of the neighborhood Space of a Winner Unit in a square and in a rhomb; in the illustration v is the degree of proximity of the K units to the WU.

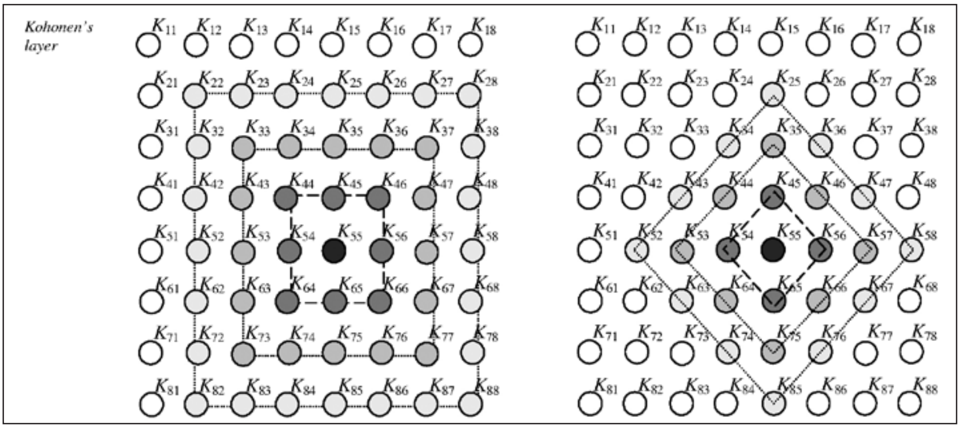


Fig. 12 – Example of the topology of the neighborhood space with matrix K (8r × 8c), where the WU is the K55 unit. The first matrix shows a neighborhood in a square while the second a neighborhood in a rhomb. We can notice from the illustration that, for example, while in the matrix to the left the v distance of the K66 unit to the WU is 1, in the matrix to the right the v distance of the K66 unit to the WU is 2.

This characteristic also allows the SOM to show the position occupied by the class within the matrix in relation to the position occupied by the other classes. This type of topological mapping, able to organize the classes through spatial relations, has been given the name of Feature Mapping.

4.9 *Topology of the neighborhood*

The neighborhood of a *WU* is defined by the degree of physical proximity (v) existing between the *WU* and the other K units. Each unit of Kohonen's layer occupies a position on the matrix of the co-ordinates (r, c) for which the neighborhood is indexed with a scalar degree from 1 to the maximum line and column dimension.

$$v_i = \pm r \quad OR \ \ v_i = \pm c$$

where max i = max r OR max c

Function *h(v)* regulates the size of the neighborhood and the extent of the corrections which need to be made on the codebooks of the units close to the *WU*. With the passing of time (cycles during which all the training set models are viewed) the neighborhood is reduced until it disappears; in this case the only unit to which the codebook is corrected is the *WU*. Since the codebooks are set during the initialization stage with random values within the layering range, the proximity of the *WU* at the beginning of the learning stage is regulated with a maximum size in order to allow all the codebooks to be modified and put closer to the Input vectors. The reduced proximity with wide matrices can determine the fact that some areas of the K matrix remain isolated because the codebooks are too different from the Input vectors. Function *h(v)* must also allow the extent of the correction to be bigger for the units close to the WU, and therefore to decrease when v is larger. The Gaussian function has been shown to meet these needs remarkably well:

$$h(v) = e^{-\frac{v^2}{\sigma}} \tag{54}$$

h (v): = EXP(-(SQR (v) / σ))

where d is the physical proximity of the unit to the *Wu* and σ is a parameter which linearly decreases by a Δ as time increases, thereby modifying the width of the curve (bell), thus the extent of the neighborhood. Figures 11 and 12 show examples of Neighborhood Space topologies:

4.10 *Correction of the codebook*

The rate of correction a codebook undergoes is determined by various factors:

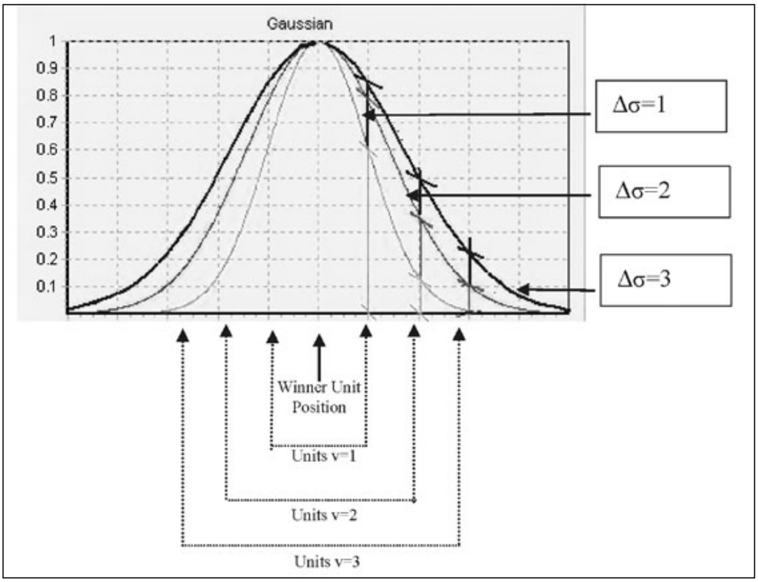


Fig. 13 – The illustration shows how, when the parameter $\Delta\sigma(1, 2, 3)$ changes – parameter that determines the correction curve of the neighborhood function – the number of units that are part of the neighborhood and the extent of the correction (v1, v2, v3) made on the weights also change.

1) Difference (d) existing between the vector codebook and the Input vector;
2) Physical distance to the WU (v);
3) Function of the neighborhood h (v) which determines a $\Delta\ \sigma$;
4) Function of weight layering in relation to the period of life of the network which determines a $\Delta\ \alpha$.

In a SOM the codebooks are moved closer to the Input vector, therefore for each generic *codebook W* the distance existing between the corresponding weights *wij* and the variables *xi* of the generic Input vector *X* is calculated. On the basis of the function h (v) of the neighborhood, the $\Delta\ \sigma$ is therefore calculated in relation to the value of the parameter s and the proximity (v) of the unit *K* to the *WU*.$\Delta\ \sigma$ is the measure which assumes y in the function *h(v)* when *x= v.* In the case in which function h(v) is the *Gaussian curve*, then the $\Delta\ \sigma$ will be calculated in the following way (Fig. 13):

$$\Delta\sigma = e^{-\frac{v^2}{\sigma}} \tag{55}$$

The $\Delta\sigma$ is calculated as a factor of a linear function decreasing in relation to the time the network is alive. Therefore, the function of correction of the codebooks is as follows:

$$f(w) = \alpha \cdot e^{-\frac{v^2}{\sigma}} \sqrt{\sum_{i=1}^{N} (x_i - w_{i,j})^2} \tag{56}$$

$$w_{i,j} = w_{i,j} + \alpha(x_i - w_{i,j} \tag{57}$$

5. A Neural Networks Theory

ANNs still need a general theory able:

1) to explain which is the place that ANNs have in the general framework of the natural sciences, and
2) to explain which are the basic and atomic features we need to assemble in order to build new Neural Networks.

We can try to give a first and an approximate answer to these questions. ANNs belong to the field of Artificial Sciences. Artificial Sciences are a new and a special branch of Natural Sciences. Artificial Sciences are the new computerized laboratories through which researchers try to simulate natural processes, in order to explain their complex and hidden laws. More specifically, ANNs are a special type of computerized laboratories able to reproduce adaptive natural processes. Under this respect, data represent a statistical sample of the natural process we intend to understand. From historical point of view ANNs have shown three different targets:

1) To understand deeply the human brain work by means of its artificial simulation. In these researches, the comprehension of human brain physiology remains the main goal and ANNs are important simulation tools;
2) To develop new computation algorithms, inspired to human brain architecture, able to processes information, more effective and fast way. In this field the main goal is to define new algorithms, and the human brain structure represents only a milestone for emulation activities.
3) To understand in every natural process how the transformation works from individual behaviors to collective behaviors. In other words, how the transition works in nature from the simple and local processes to the global and complex processes. In this case the main target of the scientist is the discovery of natural laws and the ANNs represent a set of new algorithms with which we can implement the correct experiments to control our hypothesis. In this case ANN algorithms represent a powerful experimental framework for science.

These three different fields, and especially the last one, need a general theory able to explain how to build these algorithms and/or tools in a mathematical and physical correct way. For these reasons we are thinking to a general theory of Artificial Adaptive System.

But, it is also important to elaborate a generative model able to explain how to build new ANNs, starting from the reasoned assembly of ANNs' atomic components. For this reason we propose a bottom-up theoretical process, composed of three steps (a basic layer, a central layer, and a complex layer) and two components for each step (semantics and syntax):

1. Basic layer:
I. Semantics: Node
II. Syntax: Weighted Connection.

2. Central layer:
I. Semantics: Nodes & Connections =Networks
II. Syntax: Nodes & Connections updating under specific Learning Laws and Constraints.

3. Complex layer:
I. Semantics: Organism = Networks assembly
II. Syntax: Networks interaction under specific Signal Flow rules.

Each component of this theoretical framework needs to be analyzed in details, as we tried to do in a provisory way in a previous paper (Buscema 1998); for example: the morphology of the Node and the typology of the Connections. But this could be the main goal of a next analytical and experimental research.

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ABSTRACT

This paper describes the philosophy of Artificial Adaptive Systems and compares it with natural language, revealing some striking parallels. Artificial sciences create models of reality, but their ability to approximate the "real world" determines their effectiveness and usefulness. This paper provides a clear understanding of the expectations created by the use of this technology, an evaluation of the complexities involved, and expresses the necessity of continuing with an open mind to unexpected and still unknown potentials. Supervised and unsupervised networks are described here.

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ANALYTICAL ARCHAEOLOGY AND ARTIFICIAL ADAPTIVE SYSTEMS LABORATORY (LAA&AAS)

1. Theoretical and analytical background of the LAA&AAS

The background from which the first fundamental experiments were conducted by McCulloch and Pitts (1943) and soon after those by Hebb (1949) was a neurobiological study conducted in order to interpret the neurons as logical devices. The scientific theory behind this research is known under the name of Connectionism (Rosenblatt 1958, 1962; Minsky, Papert 1968; Feldman, Ballard 1982; Grossberg 1982; Pylyshyn 1984). According to this cognitive theory, the brain is not the result of a system of rules and symbols but is composed of simple elements: neurons. Since it is the wide range of connections between neurons to express coherence properties and cognitive abilities, the connectionist approach represents a reaction to the so-called Behaviourism (Minsky 1986; McClelland, Rumelhart 1986; Ackley 1987; Fodor 1987; Grossberg 1987; Fodor, Pylyshyn 1988; Anderson, Rosenfeld 1988; Smolensky 1989). The behaviourist theory rejected the study of Artificial Intelligence based on dynamic and connective relations between neurons, and intended to interpret the logic of their operation according to a mechanical Input-Output stream (Herz, Krogh, Palmer 1991; de Callataÿ 1992).

1.1 *LAA&AAS theoretical background*

Artificial Adaptive Systems can be defined as a set of formalised structures of Natural Computation (Beckerman 1997; Mira *et al.* 2009) that describe, simulate and reproduce natural and cultural processes and/or turn them into dynamic and complex artificial processes. Indeed, recent advances in neurobiological study of the Artitificial Intelligence suggest that stochastic variation and controlled selection in programmed mechanisms can guide neural development and learning. Natural Computing is a general term referring to the computing occurring in nature and to the computing inspired by nature systems (Elman, Rumelhart 1989; Feldman, Ballard 1989; Churchland 1989; Clark 1993; McCulloch, Pitts 1993; Arbib 1995; Marcus 2001; Clark, Eliasmith 2002; Rogers, McClelland 2004; McClelland *et al.* 2010). When complex natural phenomena are observed as computational processes, our comprehension of these phenomena and of the essence of computation are enhanced. In this way we may acquire valuable insights into both natural sciences and computer science. On the other hand, the metaphorical use of concepts, principles and mechanisms underlying natural systems is characteristic of the man-designed computing inspired by nature.

This type of computing includes evolutionary algorithms, neural networks, molecular computing and quantum computing. On the methodological level, it is one of the most advanced set of techniques dealing with the problems of classification and data-mining (Ackley 1987; Bishop 1995; Tastle 2013). On the morphological level, Artificial Adaptive Systems can be further subdivided into Evolutionary Systems and Learning Systems. The so-called Artificial Neural Networks (ANNs) are organised as Learning Systems and constitute a family of algorithms inspired by the functioning of the human brain (Minsky 1954; Zadeh 1965; Hopfield 1982; McClelland, Rumelhart 1986; Grossberg 1988; Kosko 1992; Gallant 1993; Bishop 1995; Zadeh *et al.* 1996; Szczpaniak 1999; Baxter 2006; Nunes de Castro 2007).

Given this premise, the Sapienza LAA&AAS is mainly interested in experimenting/testing the theories, methods, models and algorithms of Artificial Sciences applied to the analysis of archaeological, anthropological, geographical and linguistic complex systems. From the historical point of view, therefore, these research activities are inspired directly by the mainly European methodological traditions of Computational Archaeology, Cognitive Archaeology and Analytical Archaeology (Clarke 1968; Gardin 1970, 1980, 1987, 2002, 2003; Doran, Hodson 1975; Renfrew, Cooke 1979; Renfrew 1981; Gallay 1989; Baxter 1995; McGlade, Van der Leeuw 1997; Camiz, Rova 2001; Camiz 2004; Beeckman, Baden 2005; Barceló 2007; Baxter, Cool 2010).

1.2 *LAA&AAS analytical background*

As noted, the epistemic architecture of the LAA&AAS is also interested in the strong interaction between the computing environment of Geographic Information Systems and analytical tools of non-linear dynamical systems, thus embracing some of the modern analytical tendencies that have been recently developed in the American and English Settlement Archaeology (Kvamme 1990; Allen 1999; Zubrow 2003; Kohler, van der Leeuw 2007). Therefore, although LAA&AAS is built on the line indicated in 1968 by Clarke's Analytical and Computational Archaeology (Clarke 1968, 1972, 1973, 1994), its morphology does also recognise the contemporary and now widespread and diversified cognitive approaches (Renfrew, Zubrow 1994; Djindjian 2002).

However, if the LAA&AAS deals with applied neuroscience in order to outline ancient, universal shapes and/or cognitive behavioural, contextual ones (Renfrew 2008; Malafouris, Renfrew 2008, 2010a-b), it does also develop the tools and computational models of Artificial Intelligence as a base method for the analysis of communicative, spatial and linguistic complex phenomena. The rapprochement between physic-mathematical sciences and the cognitive sciences does still present proud and sometimes intimidating obstacles, but it is also fascinating and able to open the archaeological research up to new perspectives (Ramazzotti 2010a, 199-203).

Indeed, we must always keep in mind that some of the most important scientific discoveries of the modern age were precisely achieved by adapting new technologies and meta-disciplinary testing to specific reserch contexts. For example, the study of the archaeological and geophysical environment integrated with vector maps, Geographic Information Systems, geophysical maps and automatic classification of geomagnetic anomalies led to the extraordinary discovery of the Temple of the Rock (2400-2350 BC) at Ebla - Tell Mardikh, in northern Syria (Ramazzotti 2008, 2009a, 2010b).

The linguistic and philological sphere, starting from glossematic and generative semiotics, textual criticism and the application of phylogenetic trees to texts encoded as systems allowed to reinterpret the criteria of semantic distinction in literary construction (Canettieri *et al.* 2005, 2006; Canettieri 2012); and in image analysis the study of the aesthetic and cognitive level, made through autopoietic classification systems and logical formalisation of the processes, allowed to recognise latent cultural factors in the syntax of ancient cylinder seals iconography (Di Ludovico, Ramazzotti 2008; Di Ludovico 2011) as well as ideographic codes in the construction of only apparently decorative geometric forms (Di Ludovico, Ramazzotti 2011).

Finally, the simulation of settlement processes through Artificial Neural Networks not only allowed to overcome the rigid context of the Systems Theory, offering an unexpected opportunity to expand the so-called multifactorial analysis to the earliest Mesopotamian urbanisations (Ramazzotti 1997, 1999a, 2000, 2002, 2009b), but also to design and program instruments for bottom-up predictive spatial analysis that attempt to overcome the descriptiveness of satellite photography (Ramazzotti 2013a, 2013b).

All those applications constitute a stream of approaches which depend on and follow the international success in design Artificial Adaptive Systems for key problems of contemporary researches.

2. The LAA&AAS experimental procedures

All the following experimental elaborations in the LAA&AAS have been realised in two steps: the first step was the Artificial Adaptive System Analysis, mainly applied by testing different typologies of Artificial Neural Networks on different alfanumeric databases and the second step has been the representation of the results through different graphs and tables.

Each analysis has been conducted in autonomous way but always respecting the same experimental protocol discussed in the LAA&AAS and centred on the contextual evaluation of each complex configuration results. In fact, although the ANNs are formalised mathematical structures that present highly various forms (cfr. BUSCEMA *infra*), their common characteristics can be summarised as follows:

A) The minimum elements of every Artificial Neural Network arranged in layers are nodes, elements that can be processed (Processing Elements), and connections (Weights); B) Each node of an ANN has a definable Input layer as a form of external environment interface; an Output layer and one or more interlayers, such as Hidden layers, which constitute the real Black Box network, the logical place for the learning activities of the network; C) A transformation function through which, starting from the Input signal, a global Output is generated.

2.1 *Artificial Neural Networks morphology*

Each connection is characterised by the strength through which node pairs can either excite or inhibit node pairs: positive values indicate excitatory connections, negative ones show inhibitory connections; in addition, the connections between the nodes may change over time. This dynamics triggers a learning process in the ANN: for each model the transformations of the connections are generated by an equation, conventionally called the Learning Equation.

The overall dynamics of an ANN is connected to time: in order to allow their connections to change, the processed data need to be acting symmetrically and repeatedly on the topological structure. The overall dynamics of an ANN is linked not only to the local interaction of its nodes. The final evolutionary state of an ANN must thus emerge spontaneously from the interaction of all its syntactic components (nodes arranged in layers).

Communications between nodes in each ANN tend to occur in parallel; such parallelism can be synchronous or asynchronous, but each model expresses and may emphasise it according to modalities and different shapes. Each ANN must have the following components of architecture:

A) type and number of nodes and their property;
B) type and number of connections and their location;
C) type of signal flow strategies;
D) type of learning strategies.

The nodes of each ANN can be at least of 3 types, depending on the position they occupy within the network: Input Nodes: nodes that receive (even) signals of the external environment of ANN; Output Nodes: nodes whose sign acts (even) on the external environment of ANN; Hidden Nodes: nodes that receive only signals from other nodes of ANN and send their signal to other nodes of ANN.

The number of Input nodes depends on the way we want the ANN to learn the environment/context: in this sense they can be labelled. When the environment of an ANN consists of data that are to be processed, each Input node becomes a variable type of the data. The number of Output nodes depends on the way we want the ANN to act on the environment, so the Output can be defined as network and the effector will represent the expected variables (or the results of the processing). The number of Hidden nodes depends on the complexity of the function that we want to map between Input nodes and Output nodes. Each ANN nodes can be grouped into classes of nodes that share the same characteristics (properties).

2.2 *Artificial Neural Networks topology*

Usually these classes are called layers and they involve different types of ANN: 1) monolayer ANN: when all nodes of ANN have the same characteristics; 2) multilayer ANN: when ANN nodes are grouped into functional classes, share the same signal transfer functions, but receive only signals from nodes of other layers and only send new layers; 3) spatially relevant ANN (or ANN without layers): when each node is specific to the position it occupies in ANN, for example, when the closest nodes communicate more intensely than the more distant ones. Each connection can be of five types:

1) Mono-directional;
2) Bi-directional;
3) Symmetric;
4) Anti-symmetric;
5) Reflexive.

The number of connections is proportional to the storage capacity of an ANN. The location of the connections is appropriate for the pre-processing of the methodological problem that ANN will face, but is not required. ANN in which not all connections between nodes or between layers are enabled is referred to as ANN with dedicated connections; otherwise we talk about ANN maximum gradient. In every ANN connections can be of three types:

1) Adaptive: when the learning equation changes;
2) Fixed: when the connections keep fixed values for the whole learning time;
3) Changed: when the transformation is structured in a deterministic way.

In each ANN the signal may proceed in a linear way (from Input to Output) or in complex ways. In this case, there are two main strategies: 1) ANN Feed forward: when the signal processing from the Input to the Output of ANN traverses all nodes once (Mangan *et al.* 2003); 2) ANN with Feedback: when the signal goes with specific Feedback, determined *a priori*, or tied to the occurrence of certain conditions. The ANNs with Feedback are also called ANN Recurrent (Mandic, Chambers 2001). More biologically plausible, although mathematically more complex to discuss, they are often used for temporal signal processing.

2.3 *Artificial Neural Networks learning*

Each ANN can learn over time the characteristics of the environment in which it is situated (or the data that are presented) in two ways that are interdependent with each other:

1) by reconstructing approximation to the probability density function of the data it receives from the environment, compared with pre-sorted constraints;
2) by reconstructing approximation parameters for solving the equation of connection between Input and Output data, compared with pre-sorted constraints.

The first method is known, in Artificial Intelligence, as Vector Quantification; the latter is defined as a method of Descending Gradient (Gradient Descent). The method of Vector Quantisation consists of Input variables in the Output consisting of hyper-spheres radius defined (Gersho, Gray 1992). The Gradient Descent method consists of Input variables in the Output consisting of hyperplanes (Snyman 2005).

The difference between these two methods becomes evident in the case of Feed-forward ANNs with at least one layer of Hidden units. Using the Vector Quantification, the Hidden units code locally relevant sections of the Input vector; when learning is complete, each Hidden unit is a prototype that represents one or more values of the Input vector, defined and exclusive. Using the Descending Gradient too the Hidden adapters encode the relevant sections of the Input vector, but at the end of each unit, Hidden learning will tend to represent part of the Input in a more fuzzy and not exclusive way (Bishop 1995; Baxter 2006; McClelland *et al.* 2010).

The LAA&AAS Experimental Protocols have been first applied to some problems posed by Analytical Archaeology, Spatial Analysis, and Computational Linguistics, immediately showing significant results. The simulations have, in fact, concerned very large databases that were treated using different and specific Neural Analysis Techniques: Linear Correlation, the so-called Prior Probability Neural Network and Auto-Contractive Map, the latter designed at Semeion Research Centre (Buscema, Grossi 2007, 2008; Buscema, Terzi 2007; Buscema 2008; Buscema *et al.* 2008a, 2008b).

2.4 *Artificial Neural Networks testing*

In the case of Linear Correlation, a square matrix was created for each database to represent the correlations of the registered and formalised entities in linear pairs. In the case of the Prior Probability, connections were traced to indicate the *a priori* probability of the co-occurrence of each pair of entities.

The neural network Auto-CM, at last, which is based on an algorithm that can highlight non-linear relationships between all entities understood as dynamic clusters, created a matrix containing information that is different from the information obtained through the other two types of simulation.

After these three processing, for each database the best results obtained have been selected and configured to be visualised in a graph of MST type (Minimum Spanning Tree) or in a graph whose vertices are the minimisation of energy present within a data structure composed of Atomic elements and standards that define mutual relations (Kruskal 1956; Graham 1985; Gabow *et al.* 1986; Fredman, Willard 1990). In other words, these branching graphs display the most significant associations between the entities/variables of each database – those specific relationships between entities and/or groups of entities that represent the best records of each dataset.

The analytical procedure observed had, therefore, to verify the different connective (associative) capacity of the models used, and to extrapolate those neural learning graphs with a greater complexity, not only in order to confirm the already known information, but also in order to identify new and otherwise not recognisable present or latent non-linear correlations.

3. A synthetic overview of the LAA&AAS applicative fields

The elaborations have been produced by means of a software programmed in the LAA&AAS, written in C++ language, using both the best-known Artificial Neural Networks as tools for the computing of the Minimum Spanning Tree algorithm, which is able to process the results in a format suitable for the spatial visualisation of graphs with open-source software GEPHI v. 0.8.1. The results of AAS in each applicative field can now be discussed on the epistemological and historical-cultural level.

3.1 *Technology and aesthetic of the images*

The integrated applications of GIS and AAS can also be considered a sector of the Spatial Analysis whose goal is the extrapolation of semantic constraints between the spatial-temporal distribution of archaeological features and the technological character of the objects distributed. In the LAA&AAS, technology and aesthetic of the Near Eastern clay figurines have been investigated through this integrate approach which implies the neural analysis of the semantic clusters obtained by applying geomatic technologies on the spatially referenced clay objects and/or subjects.

In particular, the GIS and AAS analysis on some clay figurines dated to Early and Middle Bronze Age and recently discovered in Tell Mardikh (Syria) displayed that during the Early Syrian period, the spatial concentration of clay figurines in the Royal Palace G of Ebla demonstrates some kind of affinity between the world of miniature clay and the sacred Kingship. On the contrary, the spatial distribution of the clay figurines during the Old Syrian Period is extensive, but the strong concentration of fragments close to the Ishtar public cult area (Monument P3 and Temple P2) seems to indicate a radical transformation of the roles played by this clay world (Figs. 1-2). It would no longer impersonate a *Mimesis* of the physical and metaphysical sacred Kingship, but rather a reproduction of the whole society (Ramazzotti 2012a).

Starting from the recognition of this semantic discontinuity, different typologies of ANNs have been tested on the 100 clay figurines, topographically referenced, in order to explore, select and classify which technological variables could be related to the spatial distribution, and to suppose from which cognitive principle the semantic transformation could be moved. The preliminary Neural Analysis displayed in the tree-graph defines a mapping of connections between variables that reconstructs the image elaboration techniques and provides material and cognitive information about the technological and psychological processes that might have occurred (Figs. 3-4). In fact, the ramifications of the graph classify three different kinds of information:

1) Since the vertices indicate one of the parts that make up the image, the largest Summit, i.e. the Summit with the highest Betweenness Centrality (Betweenness Centrality is a normalised value that represents a measure of centrality of the Summit in a generic network that is equivalent to the number of shortest paths), identifies the predominant variable in the production of these images – the incision as the most important technique for the figurative construction of the image.
2) Different classes, represented by different colours (here translated into grayscale), seem to indicate different quality groups of variables that gather to build the technological and cognitive complexity of each individual figurine; therefore, we can get a geometric hypersurface by encoding the systemic cognitive and technological complexity of each one of the 100 records processed.
3) The thickness of the lines that connect the nodes, or vertex weighted connections, indicates the measurement of the contiguity between the different variables that describe each figurine of the database (in terms of degrees of probabilistic transition), and is directly proportional to the values of the connections; these branched connections, in other words, indicate the quality and intensity of technological and cognitive relations between all the variables that have been chosen to describe every single figurine.

Thanks to this methodology not only we could then confirm that these productions of the so-called material culture were also a conscious human imitation of the sacred and royal images of power, but a very accurate reconstruction of the cognitive mechanisms underlying the specific connections between figures typologies, technologies of the images productions, and their spatial distribution will be possible in future.

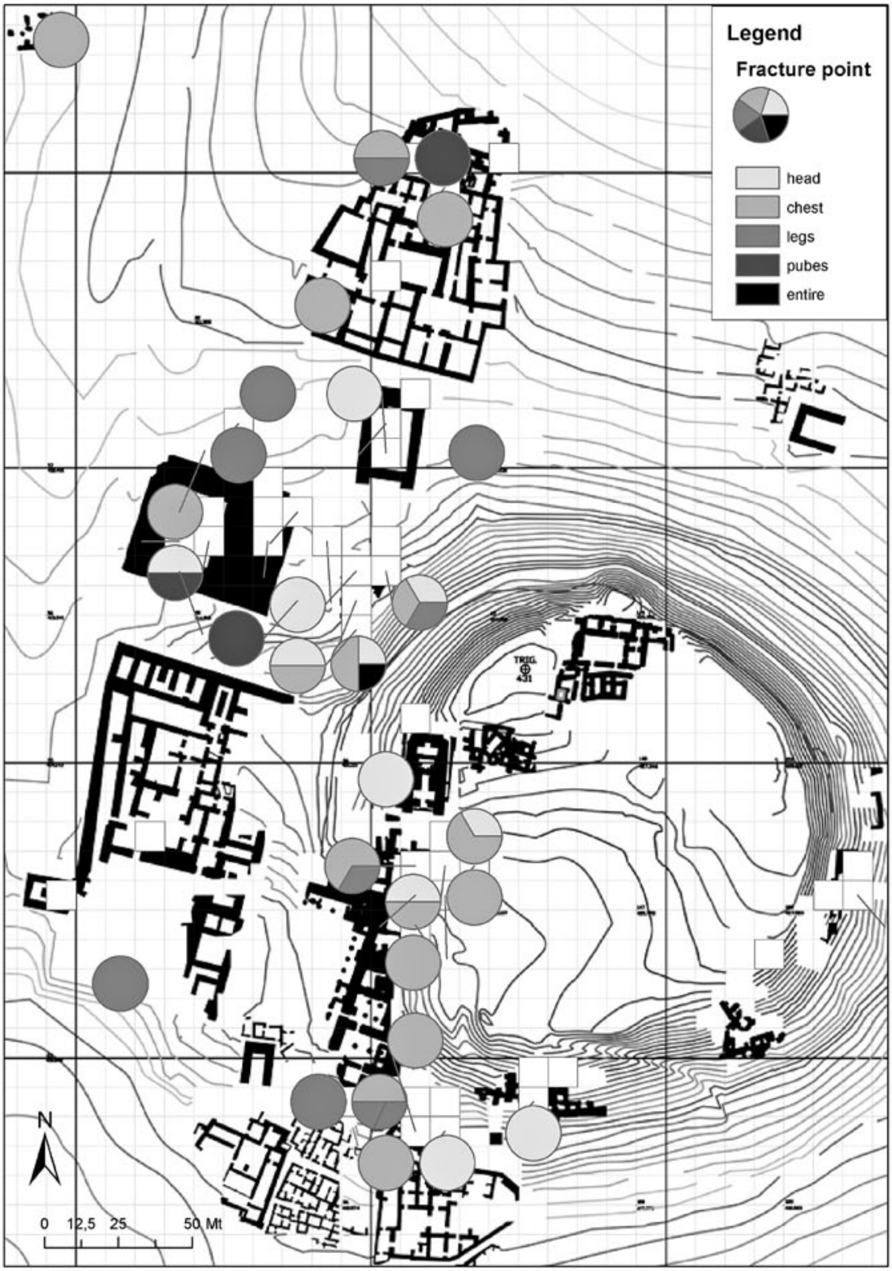


Fig. 1 – Spatial distribution of 100 clay figurines main breakages (heads; chests; legs; pubes; complete) from Ebla dated to the Early Bronze period (Ramazzotti 2014).

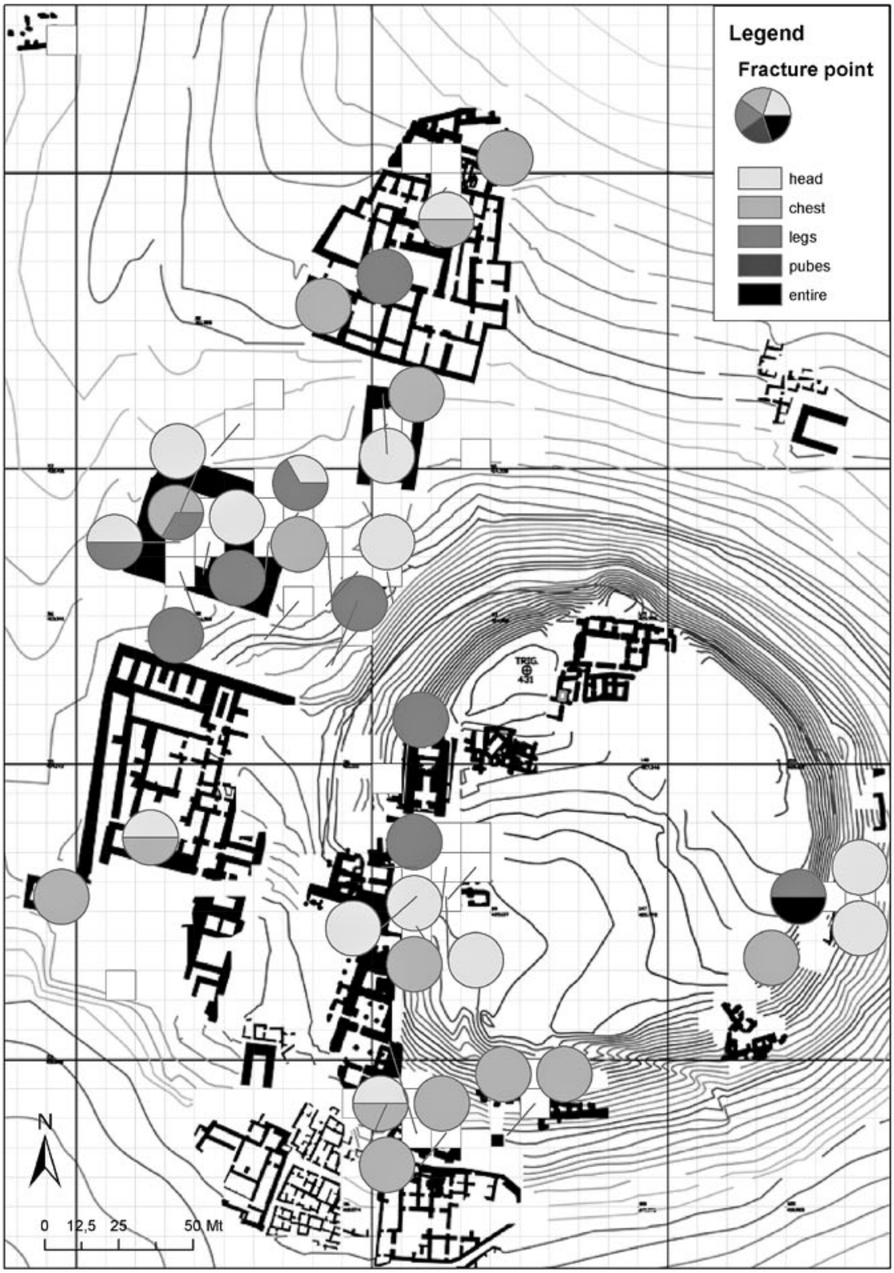
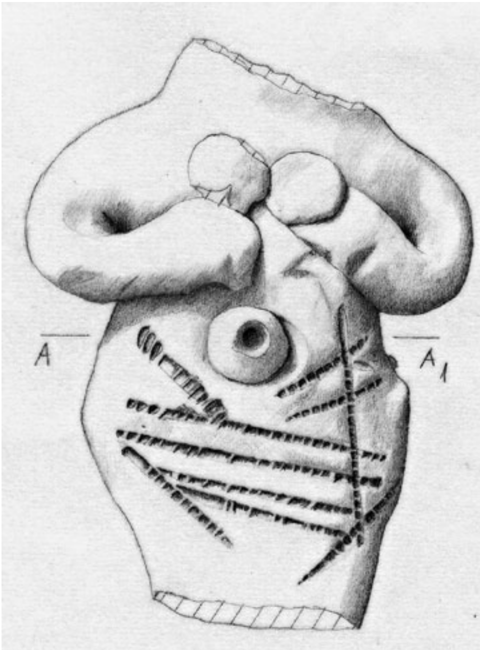


Fig. 2 – Spatial distribution of 100 clay figurines main breakages (heads; chests; legs; pubes; complete) in the Middle Bronze period (Ramazzotti 2014).



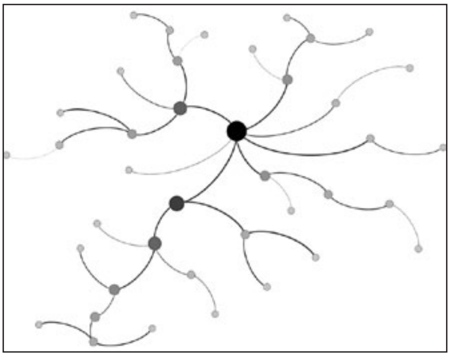


Fig. 3 – Drawing 1:1 scale of a clay figurine from Ebla in Idlib Museum (TM92P618) and dated to the Early Second Millennium BC.

Fig. 4 – The MST tree-graph defines a mapping of connections between variables that reconstructs the image construction techniques and provides material and cognitive information about the technological and psychological processes that might have occurred in Early Syrian and Old Syrian clay figurines (Ramazzotti 2013c).

Indeed, the preliminary results of the ANNs applications outline a spatial-symbolic *chaîne opératoire* of these clay objects revealing their ideographic and composite character (which can be recognised also in Early Dynastic and Early Syrian miniature composite statue tradition) and unexpected relationship between this ideographic character and its spatial distribution (Ramazzotti 2013c; 2014).

3.2 *Digital iconography and computational iconology*

The so-called Natural Computing can also be considered a sector of Cybernetics whose goal is the reproduction of some segments of the cognitive process. On the methodological level, it is one of the most advanced set of techniques dealing with the problems of seriation and data classification. Since it reproduces and expands some functions of the cognitive and perceptive behaviour, it can also be reasonably applied to the iconographic interpretation of ancient documents.

In the LAA&AAS, cylinder seals, a class of artefacts originating from pre-classical Mesopotamia, have been investigated through different computational methods – corresponding to even more numerous points of view, but a selected *corpus* of late Third and beginning Second Millennium BC glyptic scenes has been explored in depth through a perspective implying the analytical examination of their compositional patterns (Fig. 5). The ANNs allowed to locate some interactions that could be reasonably proposed as means for an interpretation of both the development of the glyptic presentation theme and

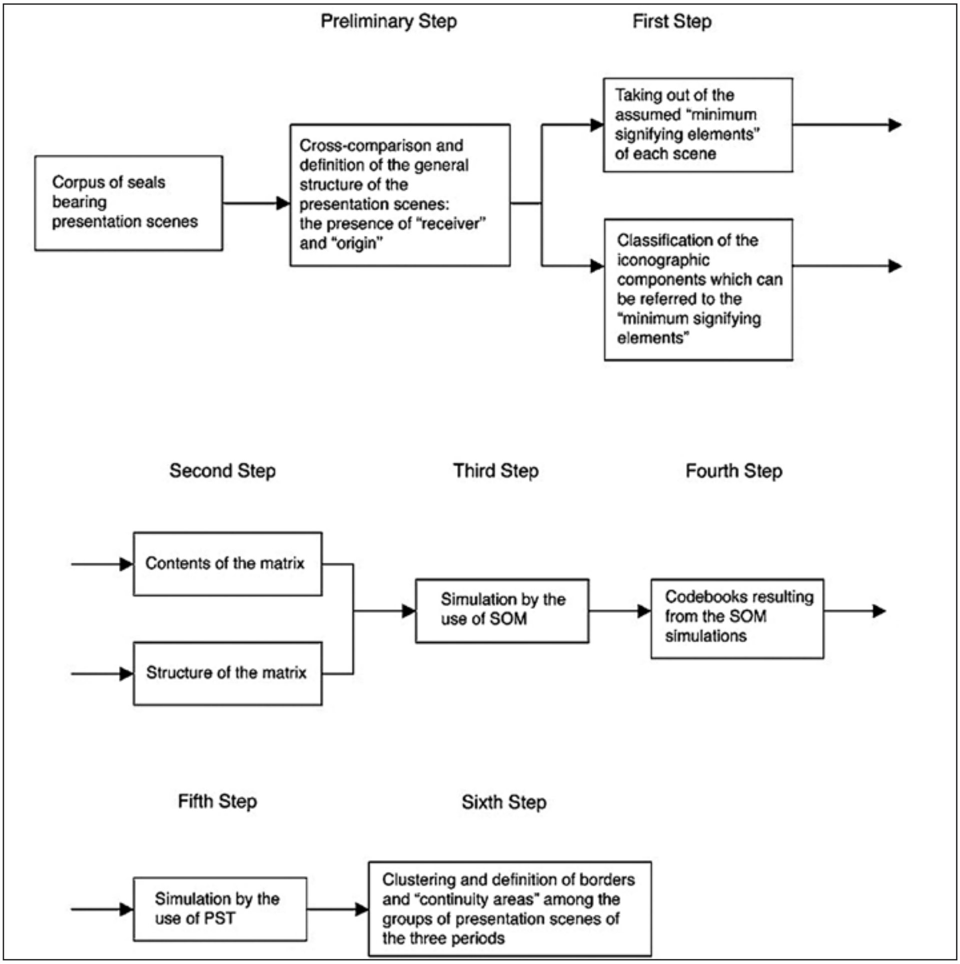


Fig. 5 – The Mesopotamian Cylinder Seals experimental process. The simulations concerned a particular Mesopotamian glyptic production dating to the Akkadian, the Post-Akkadian, and Ur III periods. After a careful formalization of the data into mathematical language, some numerical matrixes have been formed and processed using different AAS. The outline of the iconographic profile of the dataset entries led to group the Ur III presentation scenes (at the end of Third Mill. BC) into iconographic classes for which a narrative, besides a logical ground, as well as a position in the history of the logical development of the relevant theme can be postulated (Di Ludovico, Ramazzotti 2008).

the inner logical structure of single specimens (Di Ludovico, Ramazzotti 2008; Di Ludovico 2011).

The outline of the iconographic profile of the dataset entries led then to group the Ur III presentation scenes (at the end of Third Millennium BC) into iconographic classes for which a narrative, besides a logical ground, as well as a position in the history of the logical development of the relevant theme can be postulated (Fig. 5). Moreover, the analysis of a *corpus* of seals belonging to the period of Isin and Larsa carried out through the use of the Neural Network Auto-Contractive Maps, allows us to understand the complexity of the relationship of the different elements of the visual domain and its variety. The point of view here adopted is that of reading the iconography of the so-called "presentation scene" by offering an interpretation that goes beyond and transcends the concept of standardised and homogeneous production without any peculiar innovative connotations (cfr. Viaggiu *infra*).

Finally, different typologies of ANNs have already been applied to different iconological problems posed by identity recognition of the maenads and their multiple interactions with the satyrs on Athenian red-figure vases. The encouraging results of the huge amount of data have helped highlighting several interesting elements of the iconographies of maenads and satyrs. The results seem to confirm the highly interesting role of AAS methodologies as innovative tools for the organisation, visualisation and analysis of complex data in History of Art and Classic Archaeology (cfr. Wayenberg *infra*).

3.3 *Computational linguistics and dynamic philology*

For the biosemiotic linguistc theory (Gamkrelidze 2009), inspired by the so called Biosemiotic Paradigm (Uexküll 1957), an isomorphism existing between the genetic code and different semiotic systems can be traced and simulated designing natural and artificial adaptive systems (Frank 1996). If so, every kind of communications system can be studied after being transferred in a non-linear sequence of variables and can be simulated as semiotic systems to approach and to test also such isomorphism between languages and genetic codes (Ramazzotti 2010a, 88-127).

In the LAA&AAS we are testing many computational models based on AAS to explore languages as semiotic systems (Fig. 6), following many connectionist experimental approaches applied to simulate both normal and disordered word production as well as child language acquisition and symbolic grammars syntaxes (Koskenniemi 1983; Pinker, Prince 1988; Seidenberg, McClelland 1989; Faisal, Kwasny 1990; Nakamura *et al.* 1990; Pollack 1990; Elman 1991; Zipser 1991; Seidenberg 1994).

In particular, different experiments have been conducted on the ancient Mesopotamian communicative system founded on ideographic codes (Fig. 6).

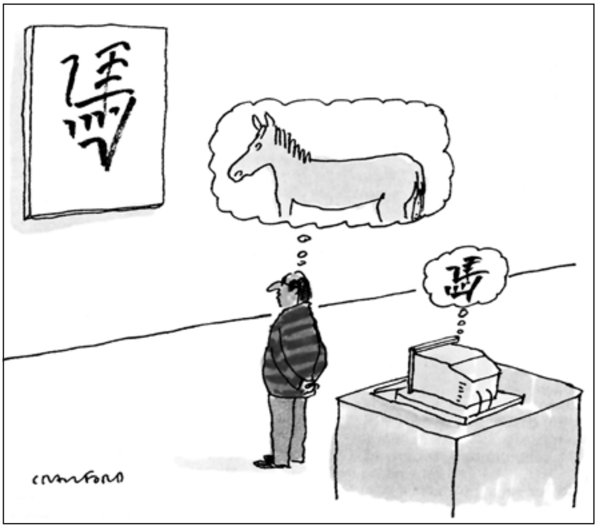


Fig. 6 – Computer programs are formal (syntactic), the human mind has mental contents (semantics) (Searle 1982).

In fact, although most scholars agree that the first ideographic writings had an administrative-economic origin, in the past a few solitary voices such as those of A. Hertz and K. Szarzyńska suggested a possible iconographic origin of the first written (Ramazzotti 2013d); and the origin of writing in the Land of Sumer has been discussed as a problem of historical epistemology dealing with «cognitive development in prehistory from the perspective of Jean Piaget's genetic epistemology, applying concepts such as the concept of sensory-motor intelligence, preoperational thought, and operational thought to the early development of human intelligence» (Damerow 1996, 1).

Since connectionist approaches have been criticised, for instance claiming that a proper linguistic method should be able to represent constituent structures and to model compositionality (Fodor, Pylyshyn 1988), in the LAA&AAS the possibility of analysing the constituent figurative structures of the first Mesopotamian ideographic writing systems has been tested. The main aim of this approach was to realise a detailed stylistic analysis of some of the pictographs engraved on the seals and this analysis identified many iconographies featuring images as related to specific ideograms signs that are present in the Sumerian cuneiform writing (Di Fede 2011).

In the next future in the LAA&AAS different typologies of AAS algorythms will be experimented in order to connect self-organised classes of the archaic figurative features of seals and *cretulae* with the first ideographic signs of the Sumerian language, and therefore to verify the suggestive theory of an iconographic origin of the first ideographic communicative systems and to detail the complex isomorphisms between images and words in Sumerian Linguistics.

Philology is a human science primarily applied to literary texts and traditionally divided into lower and higher criticism. Lower criticism tries to reconstruct the author's original text and higher criticism is the study of the authorship, style, and provenance of texts (Canettieri 2012; Canettieri *et al.* 2006). Methods borrowed from Dynamic Philology and Information Theory shows an implicit critic to the raw cladistics interpretation of the dichotomy-phenomenon (cfr. Canettieri *infra*).

In the LAA&AAS the outcome of the experiments of both text criticism and text (authorship) attribution, applied through AAS to Fernando Pessoa's texts, which represent an extreme case in the context of contemporary author's philology, were encouraging. The Pessoa archive explored through the use of ANNs, is bringing to a new light the complex and multi-layered writing system built by Pessoa, by identifying new genetic relationships among his works, useful for the construction of an overall mapping of his literary output (cfr. Celani *infra*).

Epigraphy is another human science applied to the written words and texts, but cuneiform epigraphy is a specific research field dealing with the semantic relations between ideographic codes, cuneiforms signs, texts and supports. In the LAA&AAS a sample of administrative cunieform texts from the Early Syrian state archives of Ebla were coded and processed through different models of AAS and the preliminary results of this study stress some basic issues related to the morphological and semantic structure of some Eblaite administrative records.

The first step has been oriented toward the development of a computational epigraphic methodology which could help to outline some well-grounded proposals for reconstructing the content of badly preserved clay tablets. The experimental results highlight the central role played by the physical size of the sections of each document, but at the same time they lay the foundations to rethink the typology of texts themselves and some possible sub-classifications (cfr. Di Ludovico *infra*).

3.4 *Spatial Archaeology and Human Mobility*

In the Spatial Archaeology the Human Mobility has been studied mostly through linear relationship between the settled area of the sites and the number of inhabitants. In the LAA&AAS we experimented the latest generation of AAS in order to underline a non-linear relationship between spatial distribution, morphology site, macro-economical variables and chronological sequences (Ramazzotti 1997, 1999a, 1999b, 2009b, 2013a, 2013b).

Indeed AAS are not only an ordinary complement to the spatial analysis' toolbox but they represent a new paradigm for spatial analysis and data mining. In particular Geo-SOM (Geo-Self-Organizing Map) is a tool to identify homogenous regions for which predictive analysis can be done using tools that allow the visualisation of positive and negative correlation (Viaggiu 2013). An increasingly intensified use of AAS and GIS, and the good results this method contributes to reach a more precise identification of a GIScience in general and of its research agenda in particular (Buscema *et al.* 2013; cfr. Montanari *infra*).

In the LAA&AAS this approach has been tested in order to create an artificial predictive model of the Third Millennium BC Ebla Settlement System. In particular, this methodological and applicative proposal is founded on a bottom-up predictive model of the Ebla / Chora, and it processes geographic positioning hypothesis of mausoleums of Nenaš: the most relevant and still unknown sacred place of the Ebla Hinterland, which is mentioned in the famous «Ritual of Kingship» as a step of the rite of enthronement and as a holy place of worship of the deceased kings (Fig. 7).

Specifically, the contemporary archaeological sites located on a given territory were encoded in a network of dynamic connections later tested by a series of new-generation algorithms that had already successfully been applied in epidemiology for the identification of the place of origin of some infectious diseases. The Neural Model was trained first for the recognition of the location of the Royal Tombs of Ur in the Ur and Eridu settled area, then it was experienced in the *Chora* of Ebla to generate locational hypotheses on the mausoleums' geographical position (Fig. 7a-b). This model has been built testing Minimum Spanning Tree (MST) and Topological Weighted Centroid (TWC) algorithms (Buscema *et al.* 2013) on an Ur-Eridu settlement system formalised as an Artificial Neural Network hypersurface and generated by an Auto-Contractive Map (Auto-CM).

The MST and TWC applications on an Ur-Eridu neural hypersurface has been calibrated in order to detect in the Ur-Eridu region the position of an "Event Zero", intended as the localisation of an important "Origin Area". Since we considered a strong ideological relationship between Ur and Ebla, and since we assumed a strong symbolic value of this "Origin Area", and since we experimentally observed the unexpected spatial overlapping between this "Origin Area" and the area of the Ur Royal Cemetery, we applied the same analytical methodology in order to discover another "Origin Area" in the Ebla-Chora settlement system.

If we consider this "Origin Area" an important cultural and symbolic area of the Ebla landscape (as this Origin Area was in the Ur-Eridu region), we suppose that the site isolated by the MST analysis and polygon selected by the TWC algorithm in the Ebla-Chora settlement system could reveal

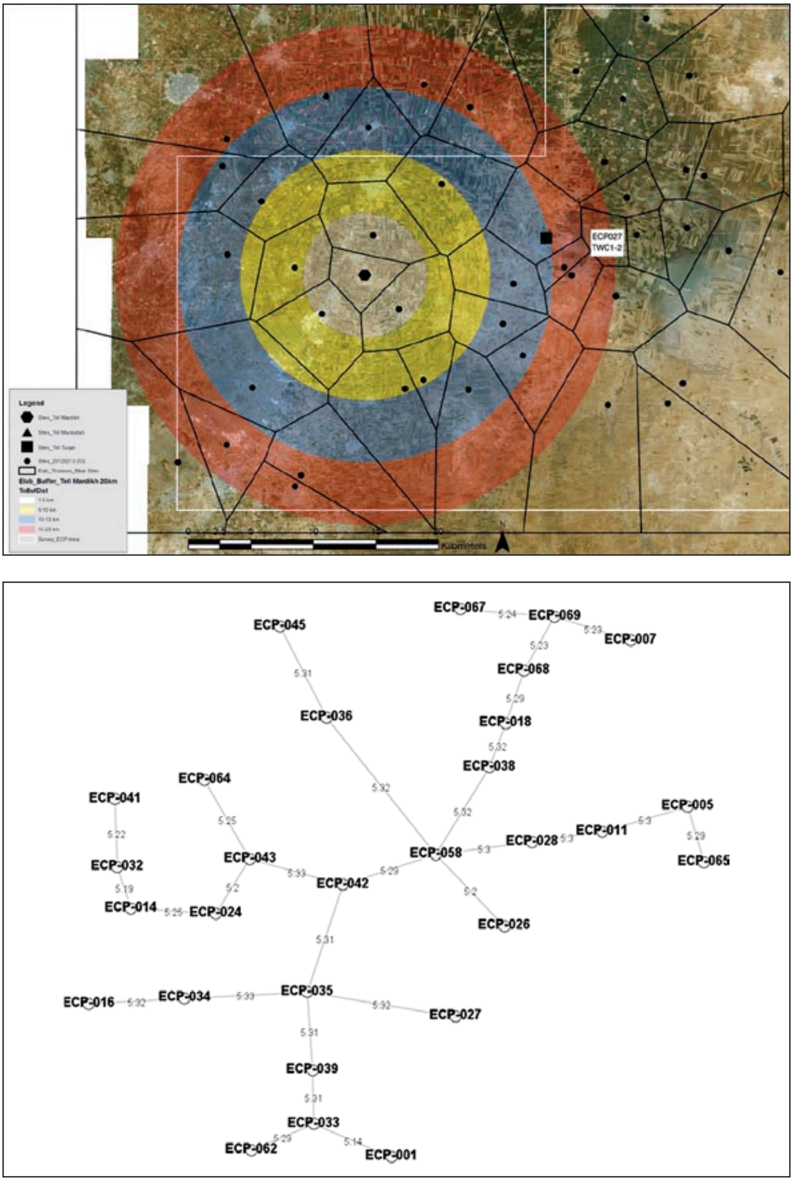


Fig. 7 – a) Thiessen Polygons map of the Ebla-Chora Survey area with the localizations of TWC 1-2 points; b) the results of MST test in the Ebla-Chora Survey area. The Ebla Chora Neural Model was trained to generate locational hypotheses on the royal mausoleums' geographical position. This model has been built testing Minimum Spanning Tree (MST) and Topological Weighted Centroid (TWC) algorithms on an Artificial Neural Network hypersurface generated by an Auto-Contractive Map (Ramazzotti 2013b).

some important "cultural and symbolic" characters, such as the well-known cultural, symbolic and religious characters of the so-called Nenaš Mausoleums, the undiscovered intermediate destination of the «Ritual of Kingship» (Ramazzotti 2013b).

3.5 *Physical Anthropology and Self-Organised classifications*

The Self-Organizing Map (SOM) is an unsupervised type of network which offers a classification of the input vectors creating a prototype of the classes and a projection of the prototypes on a n-dimensional map able to record the relative neighbourhood between the classes. The way SOM operate in reducing dimensions is by producing a map of the similarities. So SOM codebooks accomplish two functions, they reduce dimensions and they display similarities (Fig. 8).

Since the graph obtained by SOMs of a certain extent recalls a classical Multidimensional Scaling (MDS) or a Principal Component Analysis (PCA) plot, but they can handle vectors with missing components without interpolating missing data, in the Near Eastern Archaeology this autopoietic classification method has been proposed for describing non-linear high complex socio-economical systems, such as the so called Southern Mesopotamian Urbanism System (Ramazzotti 2002).

Moreover, in the LAA&AAS the SOM applications has also been proposed as an experimental biometric approach to analyse the dental morphologic relationships between archaic Homo and anatomically modern Homo sapiens (Fig. 8). The principal result indicates a close relationship between Homo erectus s.l., Middle Pleistocene specimens and the later Neanderthal groups. Furthermore, the dental models of anatomically modern Homo sapiens are particularly different compared to those of more archaic populations. Thus, SOMs can be considered a valuable tool in the field of dental morphological studies since they enable the analysis of samples at an individual level without any need to interpolate missing data or to place individuals in predetermined groups.

4. To be continued

ARCHEOSEMA (Artificial Adaptive System for the Analytical Archaeology of the Complex Phenomena) is an analytical model-procedure for theoretical and experimental researches. Applications, experiments and analyses are currently being conducted at the LAA&AAS, Department of Science of Antiquities at the Faculty of Philosophy, Letters, Humanities and Oriental Studies at La Sapienza University of Rome.

The LAA&AAS results of the project show, with evidence, that Artificial Intelligence and Artificial Adaptive Systems can be trained to detect

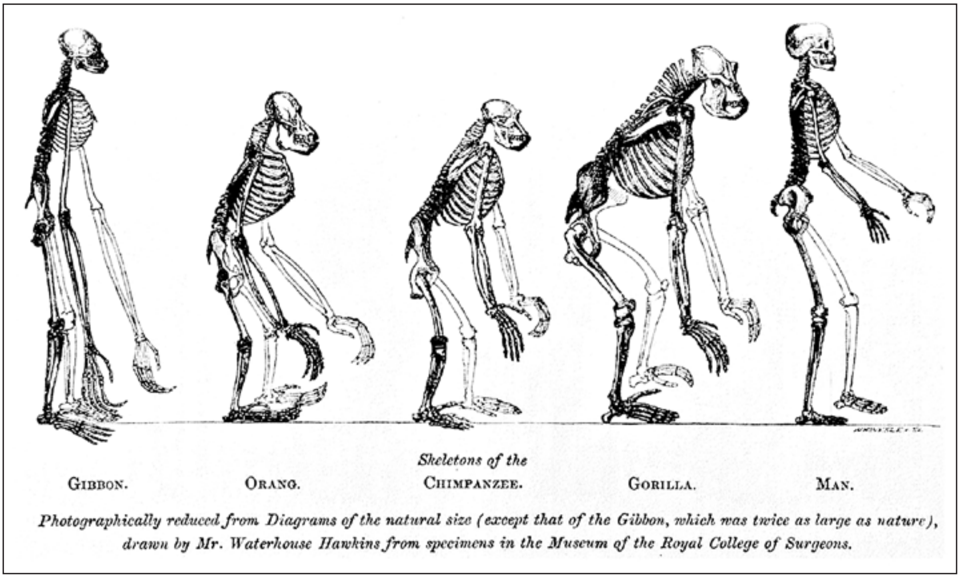


Fig. 8 – This illustration was the frontispiece of *Mans's Place in Nature* (1863). Thomas Henri Huxley applied Darwin's ideas to show that humans and apes had a common ancestor, which challenged the assumed theological thesis that humans held a unique place in the universe (Huxley 1863).

the fuzzy rules of a given complex data configuration, and may formalise this into a geometric graph that dynamically turns in relation to learning and inputs it receives. Specifically, the application of the Artificial Neural Network to the ARCHEOSEMA databases created different hypersurfaces which represent the same neural learning of each, distinct, complex data configurations. These hypersurfaces which encode some of the scientific problems posed by Analytical Archaeology, Spatial Analysis, and Computational Linguistics were subsequently translated into tree-graphs and in GIS maps that summarise the dominant semantic and spatial characters of each treated configurations.

A new exploration of these characters and/or constraints has already been introduced, and aims at an always better (and in *quantum* terms) definition of the object of investigation, and at the examination of how this object changes the shape analysis when emphasising, adding or subtracting some variables.

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ABSTRACT

This contribution represents a further attempt to synthesise and to introduce the research activities of the Analytical Archaeology & Artificial Adaptive Systems Laboratory (LAA&AAS) recently instituted at La Sapienza University of Rome thanks to the award of the project ARCHEOSEMA and to the institutional collaboration of the Department of Antiquities and the Department of Intercultural and European Studies and Physic Department. The main didactic and empirical activities of the Laboratory are related to the applicative simulations of Artificial Adaptive Systems to the analysis of complex natural and cultural phenomena through the lens of Analytical Archaeology. These complex phenomena are essentially understood to be the product of cognitive behaviour, in other words models and ideal-types which represent it and can be analysed on a formal logical level. This introductory exploration leads to a significant syntactic diversification of logical inferences and a progressive human attempt to trace them back to the simulation of cognitive complexity. Artificial Adaptive Systems, as Natural Computation mathematical tools which express these emulative properties, are historiographically involved in the connectionist reaction to behaviourism and therefore they effectively form the social sciences' attempts to ascribe the complexities developed by our brains to advanced, non-linear and dynamic computational models. The LAA&AAS results will be examined in a historical perspective, but it is of great importance to consider the epistemological implications of this new approach since it is moved by the idea that every kind of language can be studied after being transferred into a non-linear sequence of variables.

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ARTIFICIAL NEURAL NETWORKS AND COMPLEXITY: AN OVERVIEW

1. Introduction: complex systems and connectionism

Understanding the world around us is usually a difficult task. All dynamically evolving phenomena in the natural world are produced by a strong interaction among a great number of causes of which only few are visible or measurable. Moreover, the phenomena, like the weather evolution, may be so distributed over the space or time that only a small number of measurements can be done, making the understanding of the overall system difficult and approximated. In general, some characteristics of systems can produce a very strange behaviour, even when the elements constituting the system are a small number. All these elements and their mutual interaction can produce the so-called *complexity*.

In order to understand the approach a researcher may use in analysing a system, a very simple metaphor may be adopted: the iceberg. An iceberg is a floating ice mountain in the sea that shows only a small visible part above the waterline. If some specific tools are not used to improve our investigation of the iceberg, all we can describe is the movement of its visible part, the rate of melting, the colour, the transparency, and the like. Any other aspect that belongs to the submerged part is excluded from a direct measurement. Therefore, any hypothesis about the global behaviour of the iceberg can be proved by using only what we are allowed to see directly. Is all this incomplete amount of accessible information enough to fully describe the iceberg and its future evolution? This is a very difficult question to answer. All we could say is that the visible behaviour, in some sense, contains also the occulted information and everything that is out of our sight can be extracted from what is known. Even when no theories or hypotheses are allowable to create a reference framework, complex systems have the characteristic to show an evolution through the mixed actions or interactions of the variables.

In observing natural, social, economical, physical, biological systems, we basically deal with measured data that give us a partial knowledge of the "visible part" of the system. Therefore, data is required to re-build a mathematical or algorithmic framework that could be sufficiently detailed and powerful to describe the fundamental aspects of the system under study, its evolution over time, and its meaningful characteristics. A system is an organised, purposeful structure that consists of interrelated and interdependent elements (components, entities, factors, members, parts, etc.). These elements continually influence one another (directly or indirectly) to maintain their activity and the existence of the system in order to achieve the goal of the system. Although all systems have outputs, which are considered as observable variables that make possible the measurement of what the system is doing at a given time, they may also:

1) have inputs and feedback mechanisms;
2) maintain an internal steady-state (called *homeostasis*) despite a changing external environment;
3) display properties that are different than the whole (called *emergent properties*) but are not possessed by any of the individual elements;
4) have boundaries that are usually defined by the system observer.

Systems underlie every phenomenon and all are part of a larger system. Together, they allow understanding and interpretation of the universe as a meta-system of interlinked wholes and organise our thoughts about the world. If a system has no input variables, it is called *autonomous*; otherwise, if input variables can modify the outcomes of the system, it is called *non-autonomous*. Although different types of systems (from a single cell to the human body, from soap bubbles to galaxies, from ant colonies to nations) look very different on the surface, they have remarkable similarities. At the most basic level, systems are divided into two categories:

1) *Closed systems*: theoretical systems that do not interact with the environment and are not influenced by their surroundings. Only the components within the system are significant. Example: a sealed jar, nothing enters or exits the jar, but whatever is inside can interact.
2) *Open systems*: real-world systems the boundaries of which allow exchanges of energy, material, and information with the larger external environment or system in which they exist. Example: a company where, even if there are separate departments in one organisation, the workers share data and interact with each other on a daily basis.

Some other differences among systems can be found in terms of determinism. Before addressing this aspect in the world of systems, it is necessary to define the system *state*. In a system, the state describes the minimum set of inner variables that are able to uniquely describe any part of the system. When a system returns to a specific state or situation, which it already visited in the past, no differences can be found between the two situations. Therefore, two identical systems with the same state cannot be distinguished. Of course, not all the systems have inner states. If a system has no inner states, it is called a *0*-order system, and the outputs depend only on the input values. Otherwise, the presence of inner states in some way gives the system a sort of memory of the past: what happens now depends on the inputs and also on what the system did previously. These kinds of systems are called *N*-order systems, where *N* is, in some sense, the amount of memory the system beholds. Since a system's evolution over time depends on the inputs and on the past, the future outcomes of the system should also be determined by these two elements. In deterministic systems, the past and the future evolution over time are determined uniquely for a specific input. This means that if the inner state of a system is known and the input sequence in time is given, every future evolution of the system will be known and defined. From the mathematical point of view, a differential equation form represents a continuous time-deterministic system:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{F}(\boldsymbol{x}; \boldsymbol{y}(t))$$

where $\boldsymbol{x}$ is a vector containing all state variables of the system and $\boldsymbol{y}$ is a vector describing inputs explicitly depending on time (t). If $\boldsymbol{y}$ is zero, the system is autonomous. The same relation in discrete time is:

$$\boldsymbol{x}_{n+1} = \boldsymbol{G}(\boldsymbol{x}_n; \boldsymbol{y}_n)$$

$\boldsymbol{F}$ (or $\boldsymbol{G}$ in discrete time domain) is the operator linking the rate of variation of the system variables to the present state, and it can be either linear or non-linear.

In general, the evolution in time of linear differential equations is completely determined and can be calculated by means of well-established mathematical techniques. Conversely, non-linear differential equations do not have a general solution mechanism and in most cases do not admit analytical solutions. Anyway, several mathematical and geometrical techniques were developed to define the long-term evolution of this kind of equations and to outline the global behaviour of the differential dynamical system. Autonomous differential systems have steady states if there exists some combination of $\boldsymbol{x}$ variables where $\boldsymbol{F}(\boldsymbol{x})=0$. In these points, also called fixed points, the variation of $\boldsymbol{x}$ is null and the system will keep this steady state until some perturbation is applied from the external environment (*input*). The stability of the fixed points is described by the dynamical behaviour of the surrounding space. The local space can be studied by a linearization of the dynamic system, and the general behaviour of the system around the fixed point can be evaluated by means of the main directions of convergence or divergence (*eigenvectors*) and their associated eigenvalues (Robinson 2004).

Linear differential equations, as dynamic outcomes, can produce only fixed stable or unstable points and oscillations instead of more complex geometric objects (both in two or higher dimensions). Conversely, non-linear differential systems can show a greater amount of time evolutions, some of which are definitely more strange and difficult to deal with. In three or more dimensions, all previous cases can appear but additional behaviours may be added to the geometric taxonomy of *attractors* (Guckenheimer, Holmes 1983; Khalil 2001; Jordan, Smith 2007). An attractor is a set of points in the phase space where all trajectories starting in a sufficiently close state will converge. The set of all points fulfilling this request is called basin of attraction. Therefore, the attractive fixed points and orbits shown in two-dimensional examples are attractors. As mentioned in the previous part, since the dynamic evolution is considered deterministic, two different trajectories cannot intersect each other to preserve the uniqueness of the future system evolution. Starting with this consideration, one may ask what kind of new attractors may emerge from a high-dimensional non-linear system. Around 1970, physicists and computer scientists encountered a special kind of attractors that, even if they were describing a deterministic system, they could not forecast the long-term evolution (or limit behaviour) unless considering a new geometrical object called fractal. This kind of time evolution of a system was named *chaos*. Some examples of chaotic attractors are the Duffing oscillator, the Lorenz system, or the Chua's circuit.

A chaotic attractor shows a geometrical form similar to a ball of thread. Trajectories pass very close to each other but they never intersect, preserving the deterministic nature of the system. It can be proved that trajectories, belonging to the chaotic attractor, do not fill the space in which they are embedded in a uniform way. In previous cases, an attractive fixed point has a dimension equal to zero, an orbit has a dimension equal to one (length), surfaces are two-dimensional, volumes three-dimensional, and so on. Chaotic attractors have a non-integer dimensionality, since they do not fill the space uniformly and densely. For instance, the Lorenz attractor has a geometrical Hausdorff dimension equal to 2.06 (Falconer 1985). It means that the trajectory fills the space more than a 2-dimensional surface, but the density of points is not sufficient to fill the space as a dense volume. This is the reason why these attractors are called strange or fractal.

Another feature characterising the strange attractors is the local divergence of close trajectories. Because of the geometrical aspects of this kind of strange objects, two close initial states are expected to move away from each other with an exponential law of divergence. The rate of local divergence is measured by the so-called Lyapunov exponent (Barreira, Pesin 2007). Therefore, even if the chaotic attractor geometrically describes the global behaviour of the system and the trajectory remains in that part of the space, when the system explores a state, which is close to another one visited in past, its evolution is expected to be very different after some time. The effect of diverging trajectories is called, by using a metaphor, the *Butterfly Effect*. This effect explains the dependence of the system evolution on small indetermination of the initial state. As a matter of fact, the calculation of a dynamic system time course requires infinite precision in the knowledge of the initial state. If either a small perturbation or simply a rounding operation were applied to the initial state, the future evolution of the trajectory would be expected to diverge from the predicted one.

Therefore, the Butterfly Effect describes the fundamental importance of small perturbations in the knowledge of the initial states. The name of the effect, coined by Edward Lorenz, is derived from the theoretical example of a hurricane's formation being contingent on whether or not a distant butterfly had flapped its wings several weeks before (Lorenz 1996). Finally, another feature characterising the chaotic attractors is that a chaotic evolution is neither periodic nor quasi-periodic (i.e., sum of several periodic evolutions the frequencies of which have irrational ratio). Therefore, chaotic evolutions are hardly distinguishable from random evolutions, and the time series coming from chaotic systems may be misinterpreted as unpredictable noise. The power spectrum of chaotic signals reveals continuous dense zones, similarly to noisy and weakly self-correlated systems. According to the existing literature, non-linear dynamic systems are deterministic but manifest their time evolution in a way that is very difficult to describe, analyse, and predict. Long-term prediction is to be fully excluded, even if the deterministic machine gives the possibility to extract some useful and interesting parameters to identify the systems (Ruelle 1989).

Complexity can therefore be summarised by mixing the following factors: high number of dimensions (or descriptive variables), non-linearity in description of differential equation systems, some noise, which may come naturally from environment, from exclusion of any marginal aspect of the system description, or from measurement errors. Complex systems are therefore characterised by strange, non-periodic, unpredictable time evolution, strong inter-relation among variables, sensitivity to initial condition, and difficult discrimination by noisy non-deterministic phenomena. One may ask the reason why it is so interesting to define, identify, analyse and understand complex systems.

The answer lies in the fact that most natural systems are ruled by non-linear differential equations. When these systems are non-autonomous and admit inputs from external stimuli, a very complex evolution may be difficult to define: the amount of chaos may change over time and the understanding of these phenomena becomes difficult. The traditional tools as statistics or classical mathematical approaches can fail to give sufficient information about the nature of what was observed. It has been proved that weather prediction (Lorenz 1963), socio-politic systems (Campbell, Mayer-Kress 1991; Pere *et al.* 2006), economic markets (Guégan 2009), stocks (Levy 1994), currency markets (Chorafas 1994), biological and ecological natural systems (Stone, Ezrati 1996), among others, are ruled by chaotic equations that, even with a small set of variables, can show complex and unpredictable evolution.

Complex systems represent a new approach, which studies how relationships between parts give rise to the collective behaviours of a system and how the system interacts and forms relationships with its environment. The equations from which complex system models are developed generally derived from statistical physics, information theory, and non-linear dynamics, and represent organised but unpredictable behaviours of systems of nature that are considered fundamentally complex. The physical manifestations of such systems cannot be defined; thus, the usual choice is to refer to "the system" as the mathematical information model without referring to the undefined physical subject that the model represents. The key problems of complex systems are difficulties with their formal modelling and simulation. From such a perspective, in different research contexts, complex systems are defined based on their different attributes. Since all complex systems have many interconnected components, the science of networks and network theory are important aspects of the study of complex systems. A consensus regarding a single universal definition of complex system does not yet exist.

For systems that are less usefully represented with equations, various kinds of narratives and methods are used to identify, explore, design and interact with complex systems. Some definitions of complexity focus on the question of the probability of encountering a given condition of a system once characteristics of the system are specified. The complexity of a particular system is the degree of difficulty in predicting the properties of the system, given the properties of the system's parts (Weaver 1948). In Weaver's view, complexity comes in two forms: disorganised complexity and organised complexity. Disorganised complexity results from the particular system having a very large number of parts, say millions of parts, or many more.

Although the interactions of the parts in a disorganised complexity situation can be seen as largely random, the properties of the system as a whole can be understood by using probability and statistical methods. Organised complexity, on the other hand, resides in nothing else than the non-random, or correlated, interaction between the parts. These correlated relationships create a differentiated structure that can, as a system, interact with other systems. The coordinated system manifests properties not carried or dictated by individual parts. The organised aspect of this form of complexity can be said to "emerge" without any "guiding hand". The number of parts does not have to be very large for a particular system to have emergent properties. The properties of a system of organised complexity may be understood through modelling and simulation conducted particularly with computers.

A very important aspect of complexity can be found in the field of *connectionism*. Connectionism comprises a set of approaches in artificial cognition modelling that models mental or behavioural phenomena as emergent processes of interconnected networks of simple units. The key word linking complexity and connectionism is "emergence" because the strange and complex phenomena that may arise from non-linear world are, in some sense, unexpected from the point of view of classical system analysis. For instance, the complex behaviour emerged in Lorenz model of weather was so unexpected that the author himself was convinced that it was an error in the implementation of the algorithm. The non-linear relationships between weather single elements and between the neural cells in the brain have in common the possibility of the emergence of unexpected and extremely interesting behaviour. The interesting part of complexity in brain structures is well known, as it involves the emergence of efficient approaches to solve difficult tasks that traditional algorithmic techniques fail to describe even the simplest cases. In the last years, several problems have been addressed using techniques inspired by natural connectionism: face recognition (Le 2011), language recognition (Cole 1989), automatic robot guidance (Gowdy *et al.* 1991), pattern recognition (Ripley 1996), economic prediction (White 1988), and many others.

Another aspect of connectionism related to complexity is the network of interconnected simple units. Any interconnected structure of dialoguing elements that influence the future is related to the behaviour of some set of neighbour elements of the same kind and is likely to show complex behaviour in its time evolution. Once again, such a complex behaviour is given either by the eventual non-linear relationships among elements, by their inner non-linear dynamics, or by the great amount of elements synchronically evolving in time.

In brain, for example, the complex dynamics can be measured in several cognitive states but, at the same time, some sort of cooperative coherence can be relevant depending on the task that the specific cortex area is performing. Different kind of coherence and different kind of chaotic evolution can relate to different kind of cognitive states and perceptions. According to what previously described, complexity is an attribute of connectionist systems. Therefore, simple non-linear processing units connected to each other according to some defined rule can be considered as the fundamental elements for building a complex system the-behaviour of which may reflect the complexity of a target system under investigation (Sporns *et al.* 2000).

2. Neurons and synaptic connections

The simple units that comprise a neural network are called artificial neurons, whose behaviour is based on the biological neurons by means of the functions performed by the latter operating in their natural environment. What we know about biological neurons is due, among the others, to the pioneering work of Ramón y Cajál (1911) who introduced the idea of neurons as structural constituents of the brain. Typically, neurons are rather slower than silicon logic gates, but the brain compensates the relatively slow rate of operation of a neuron by having a truly staggering number of neurons with massive interconnections between them. It is estimated that there are approximately 10 billion neurons in the human cortex and 60 trillion synapses or connections.

The result is that the brain is an enormously efficient structure. Synapses are elementary structural and functional units that mediate the interactions between neurons. The most common kind of synapse is the chemical synapse. When a presynaptic process liberates a transmitter substance (*neurotransmitter*), it diffuses across the synaptic junction between neurons and then acts on a postsynaptic process. Therefore, a synapse converts a presynaptic electrical signal into a chemical signal and then back into a postsynaptic electrical signal. In terms of physics language, a synapse operates as a one-directional gate in which information or signals may flow in only one direction. A synapse can have excitatory or inhibitory function on the receptive neuron but not both.

The modification of synaptic configuration is called *plasticity* in neurobiology. Plasticity permits the developing nervous system to adapt to its surrounding environment. In an adult brain, plasticity can operate by means of two mechanisms: the creation of new synaptic connections between neurons and the modification of existing synapses. The former part will be implemented in the phase of building the structure of an ANN while the second part will be used in the training phase of a neural system. Bioelectrical signals reach the synaptic zones, flowing into a special transmission line called axon. Axon is the unique output of a neuron, and the signal flowing into it is supported without leakage by the axonal transmitting system until it reaches the synaptic terminals. As mentioned before, a given amount of neurotransmitters is released and by diffusion, the neurotransmitter molecules reach the receptive sites of the postsynaptic neurons in specific neural structures called *dendrites*. The basic mechanisms underlying the functioning of a neuron can be summarised as follows:

1) The external stimuli reach the neuron inputs by means of the synaptic transmission. The efficiency and the nature of every synaptic site determine the amplitude of the signal read by the neuron cell.
2) All the inputs are integrated to define the internal membrane potential.
3) If the membrane potential is greater than a reference threshold potential, an action potential is generated as a sequence of spikes that is transmitted along the axon (output channel).
4) The action potential reaches the terminations where the phenomenon of neurotransmitters diffusion is repeated and the synaptic sites of the postsynaptic neurons can again read the neuronal stimulus at their inputs.

Here, we identify three basic elements of the neuronal model:

1) A set of synapses, or connecting links, each of which is characterised by a weight or connection strength. Specifically, a signal x_j at the input of synapse j connected to neuron k is multiplied by the weight w_{kj}. The first subscript refers to the neuron in question and the second subscript refers to the input end of the synapse to which the weight refers. Unlike a synapse in the brain,

the synapse weight of an artificial neuron may lie in a range that includes negative as well as positive values.
2) An adder (S) for summing (or integrating) the input signals weighted by the respective synapses of the neuron. The operation described here constitutes a linear combiner.
3) An activation function (j) for limiting the amplitude of the output of a neuron. The activation function is also referred to as a squashing function, since it squashes (limits) the permissible amplitude range of the output signal to some finite value. Typically, the normalised amplitude range of the output of a neuron is written as the closed interval [0,1] or alternatively [-1,1].

As stated in Amit (1992), some unexpected perturbations may influence the output of a neuron. Basically, several sources of incoherent mechanisms may be identified in the field of biological processes of neurons. These perturbations may be due to small fluctuations of neurotransmitter densities in synaptic vesicles, by the quantised aspect of neurotransmitter molecules, and by unpredictable fluctuations of biological elements, as for instance hormones, in the area where the neuron is functioning. The total influence of these unpredictable causes of noise follows a Gaussian statistical distribution. Since the amount of activity of a neuron is given by the frequency of spiking pulses, we can say that the number of spikes in the unit of time is proportional to the probability of activation. A spike is transmitted if the activation potential is greater than the threshold; therefore, the activity of a neuron can be formulated in terms of probability depending on the local field. The mathematical relation linking the activation probability and the local field defines a characteristic function, widely used in ANNs, usually called sigmoid or logistic function.

3. ANNs: structure and training

In 1952, Frank Rosenblatt, a psychologist and researcher at the Cornell University, invented an algorithm to perform a simple learning by an artificial neural network (Rosenblatt 1958). Since Rosenblatt attempted to model a sensory system of the brain, this typology of neural network was called *Perceptron*. The basic idea was that human beings learn to enter information and concepts by using common senses (mainly sight and hearing) and store the information in some kind of memory, such that when specific information is recalled, it has to be equal to the original one. If the recalled information were learnt incorrectly, it would be necessary to learn such information again so that the new recall operation would have a higher probability to be correct compared to before. This approach can be repeated until all input information is correctly stored and classified, if possible. A neural network that is able to process such information should have a suitable number of inputs for reading the proposed information and an appropriate number of outputs for describing the class to which it belongs.

A crucial aspect of connectionist models is their ability to learn by experience. Even in the case of Perceptron, Rosenblatt (1958) proposed an algorithm named Delta Rule to define the suitable set of synaptic weights and biases for correctly classifying a set of input-output relations. If the response of an output unit is incorrect, the network can change to produce the correct response the next time that the stimulus is presented. The activity of a neuron is determined by the sum of inputs leading to it and each input is given by the product of the activity of a presynaptic unit multiplied by the weight of the connection between them. This means that any change in connection weights will change the activity level of units in the next layer. Thus, an output unit with activity that is too low can be corrected by increasing the weights of connections from units in the previous layer that provide a positive input to it and by decreasing the weights of connections that provide a negative input. Output units with an activity that is too high can be corrected by the opposite procedure.

The fundamental aspect of the Delta Rule is that, in the case of binary units, it cannot be applied to multilayer networks. In a multilayer network, desired output of hidden units is unknown information since we want to train the network based on the final output values, which are the values of the last layer outputs. Therefore, Delta Rule can be applied only to a single layer Perceptron for linearly separable tasks. Novikoff (1962) proved that the perceptron Delta Rule algorithm converges after a finite number of iterations if the dataset is linearly separable. A more general approach can be pursued by considering the relationship between the overall errors of the network related to the patterns presented at the input. When all P patterns are presented to the network, the overall error can be calculated as:

$$E = \sum_{p=1}^{P} E^{(p)} = \frac{1}{2NP} \sum_{p=1}^{P} \sum_{i=1}^{N} \left(t_i^{(p)} - y_i^{(p)}\right)^2$$

where $t_i^{(p)}$ and $y_i^{(p)}$ are, respectively, the desired and the actual network outcomes for the p-th presented input pattern, and N is the number of outputs. Note that the error E is always positive unless the network outcomes are identically equal to the desired output, and in this case, the error is zero. Since $y_i^{(p)}$ depends on the network synaptic weights, as well as on the presented pattern at input, the general error E may be modified by changing the synaptic inner parameters of the network. In particular, if a given modification of a synaptic weight Δw eliminates the output error when a certain pattern is presented, such modification may be considered as a useful contribution to the training. Thus, the error will be lower the next time the pattern is presented. In order to achieve a better comprehension of the pattern by the network, a positive increment of the weight should be associated with a negative error variation, that is, a decrease in the error. In mathematical terms:

$$\Delta w = -\eta \frac{\partial E}{\partial w}$$

where η is a constant training parameter. This approach is called the Least-Mean-Squares procedure introduced by WIDROW and HOFF (1960). According to the presented information, the feed-forward can be trained with Widrow-Hoff procedure, providing that sigmoid activation function model describes the units. Anyway, in a neural network, the error reduction can be achieved only by taking into account the whole set of synaptic weights, unlike the Widrow-Hoff procedure that can treat only the single neural layer case. This issue is avoided by the Back-Propagation training algorithm, which is based on the Widrow-Hoff approach and allows for estimating the expected values of the hidden neurons by reconfiguring the Widrow-Hoff algorithmic technique. Two main steps basically characterise Back-Propagation training algorithm:

1) The computation of the function signal appearing at the output of a neuron, which is expressed as a continuous sigmoid function of the input signal and synaptic weights associated with that neuron.
2) The computation of an estimate of the gradient vector, which is needed for the backward pass through the network.

The objective of the training process is to adjust the free parameters of the network to minimise the average error. To do this minimisation, the Back-Propagation algorithm, introduced by Rumelhart, Hinton and Williams (RUMELHART *et al.* 1986), can be used to exploit the backward error signals to overcome the limit of the Widrow-Hoff approach in case of multilayer networks. Specifically, we consider a simple method of training in which the weights are updated on a pattern-by-pattern basis until one epoch, that is, until one complete presentation of the entire training set has been dealt with. The weights are adjusted in accordance with the respective errors computed for each pattern presented to the network. The Back-Propagation algorithm is used to determine the value of the local gradients of a neuron of a specific hidden layer according to the local gradients of the next layer on the right. The local gradient of every hidden layer can be calculated *backwards* starting with the knowledge of the local gradient of the hidden layer at its right side (obviously the last hidden layer local gradient is calculated on the basis of the output layer). We now summarise the relations derived for the Back-Propagation algorithm. First, the correction Δw_{ij} applied to the synaptic weight connecting neuron i to neuron j is defined by the delta rule:

(Weight correction Δw_{ij}) = (Learning rate parameter η) × (local gradient δ_j) × (input signal of neuron $j\, y_i$).

Second, the local gradient δ_j depends on whether neuron *j* is an output node or a hidden node:

1) If neuron *j* is an output node, δ_j equals the product of the derivative $F'(v_j)$ of the sigmoid function defined in its state, and the error signal e_j, both of which are associated with neuron *j*.
2) If neuron *j* is a hidden node, δ_j equals the product of the associated derivative $F'(v_j)$ and the weighted sum of the δs computed for the neurons in the next hidden layer or output layer that are connected to neuron *j*.

When applying Back-Propagation algorithm, two distinct passes of computation are distinguished. The first pass is referred to as the forward pass, and the second is referred to as the backward pass. In these recent years, the gradient descent approach, proposed by Widrow-Hoff procedure and applied via error Back-Propagation to a multilayer neural network, has undergone numerous improvements and variations aimed at a more reliable searching for the minimum. One of the most efficient modifications of Back-Propagation algorithm is the Levenberg-Marquardt approach (Marquardt 1963), also called Levenberg-Marquardt Back-Propagation (LMBP), which was applied to multilayer neural networks by Hagan and Menhaj (1994).

Recurrent Neural Network is a class of neural networks where connections between units form one or more cycles. This creates an internal state of the network, which allows it to exhibit a dynamic temporal behaviour. Two of the most popular networks belonging to this class are the Elman network and the Jordan network (Cruse 2009). The Elman network is very similar to a multilayer feed-forward neural network, except for the presence of some context units forming a supplementary layer. At their inputs, the context units receive the outcomes of specific hidden layer units and send their outcomes to the inputs of the same hidden units again.

These connections form a cycle of information that flows into the network while the network outputs change in time and the input information remains constant. The network is then characterised by an internal dynamics and the output depends not only on the information presented at the input gates, but also on the internal network state. The outcomes of the Elman network are considered the real network responses when the relaxation process converges to an internal steady state. The Jordan network is similar to Elman networks. The context units are however fed from the output layer instead of the hidden layer. The recurrent neural networks take advantage of the presence of a memory of the recent past (internal recursion) to address complex problems in which the temporal aspect is crucial for achieving excellent results, such as handwriting recognition or spoken recognition.

The Hopfield Network was the first attempt to realise an associative memory by means of a connectionist model. Hopfield proposed a network where each binary unit is connected to all the remaining units in the network (fully connected network), although no auto-connection are allowed (Hopfield 1982). Then, for *N* neurons, the amount of required connections is *N*(*N*-1). The connection weights are defined according to the Hebb's law (Hebb 1949). The Hebb's law is a rule according to which the connection weight between a pre- and a post-synaptic neuron tends to grow when the activity of the neurons is coherent (that is, they are operating in the same state) while it decreases when there is incoherency between the units state. Starting with this aspect, Hopfield stored in this network some input patterns by determining the weights change according to the coherence/incoherence between all units that had to represent the specific "pixel" (or bit) of all the considered patterns.

After defining the network according to its connection weights, when the neurons are initialised to an initial configuration and successively allowed to evolve freely, the network tends to converge its internal dynamics to one of the memorised patterns after a relaxation time. This network was largely used for pattern correction and associative storing of information. Several networks were proposed, starting with the Hopfield original idea to overcome some particular drawbacks of the Hopfield network, such as the poor storing capacity, the patterns of orthogonality constrain, and the presence of undesired memorised phantom patterns.

Self-Organizing Map (SOM) is a neural network that is trained using unsupervised learning to produce a low dimensional (typically two-dimensional), discretised representation of the input space of the training samples called a map. As opposed to the training algorithms used for feed-forward networks, the unsupervised learning does not require an external observing system to define the distance between the correct and the actual output pattern to modify the connection weights; instead, it is based on implicit internal rules usually aimed at performing a suitable representation of the significant features of information. Kohonen (1982) proposed the most popular and widely diffused Self-Organizing Map (SOM) connectionist model. This network is based on the Winner-Takes-All (WTA) mechanism and the local training of the units spatially closed to the winner neuron. These approaches can be very powerful in defining a strategy for finding the closeness between patterns and representing it in a low dimensional space. This characteristic is similar to the result of application of statistical Principal Component Analysis (PCA) but unlike it, the neural process is typically non-linear and the description power of a SOM can be considered as more reliable and robust with respect to the traditional approaches.

4. Representation of the world by ANNs

As stated in the introduction, Artificial Neural Networks have to behold the ability to give a representation of the relations between input and output stimuli in order to assign a sufficiently general model of the system whose data are elaborated. By following the metaphor of the iceberg, data are only the observable, usually dynamic, reduced manifestation of the system, but are supposed to behold the full information about the dynamic temporal and spatial structure of the system. By heuristic observations, simple problems can be solved by neural networks whose structure is, in some sense, as simple as the problem complexity level. Conversely, problems with a high level of complex behaviour can be addressed only if the network reflects such a complexity in its connectivity. This principle is one of the bases of the neural Darwinism stated by Edelman (1987). The main thrust of his theory of neural Darwinism is that the brain is a somatic selection system similar to evolution, and not an instructional system. Here, somatic means that selection is over the time scale of a living body instead of being on the time scale of evolution.

The main difference between an instructional system and a selectional system is that the instructional system uses information from the environment to change the properties of the object in question, but a selectional system has a large and varied population of objects, and the ones that are most fit for the environment are differentially reproduced. According to Edelman, the natural evolution is the most efficient search algorithm in its proper domain, but similar selectional dynamics are present in many other systems, like immune system and natural neural networks. What selectional systems give us that instructional systems do not, is the fact that they do not require any prior knowledge of the environment, and no explicit information transfer from the world.

Whereas with the instructional system, the question of who or what *decides* what is important for the system to learn is in general unresolved. This leads to the endless regression of homunculi, implicitly contained in training algorithms (supervised training algorithms as Back-Propagation where a supervisor decides the modification of the network weights as a result of the comparison between desired and actual output, and unsupervised training algorithms as in SOMs where the algorithm structure itself is externally imposed and based on the similarities between input data and the network prototypes).

The strength of Edelman theory relies on the independence of an external controller deciding *a priori* the structure of the network which defines the ability of the neural system to address the specific task, basing on what reported previously. The complexity of the network, in terms of connectivity, is then ruled by an evolutionary process, which tend to select the best neural structure to optimise the behaviour in the virtual environment defining the problem task. From this point of view, the evolutionary approach fulfils the request that a complex task must be addressed by a sufficiently complex algorithmic process, in this case an artificial neural network, whose structure is generally unknown and depends only on the intuition and experience of the researcher. Similar considerations have been made also in the field of cognitive psychology (Olivetti-Belardinelli 1986). The human mind builds the representation of the world by consequence of the evolutionary process, which led to the actual connectivity of the brain, and the mechanisms governing the learning process of neural networks as the Hebbian synaptic weight modification rule and the brain plasticity.

The concept of a brain, or more simply, a neural network whose connectionist structure is governed by evolution over populations of neural network generations is at the base of several modern efforts in neural network research, attempting to overcome the classical approaches where the network structure is defined, by leaving the evolutionary algorithm evolving in terms of connectivity and, in some cases, weights distribution in order to catch and correctly represent the complexity of the system under analysis (Montana, Davis 1989; Zhang, Mühlenbein 1993; Fiszelew *et al.* 2007). At present, some interesting projects are involved in building a massive neural computer (Migliore *et al.* 2006), containing a hundred billions of artificial dynamic neurons and allowing a connectivity at any range order, whose connectionist structure is either inspired and led by natural brain areas observation or governed by evolutionary algorithms to detect efficient and reliable network structures for the task proposed to the artificial system (Izhikevitch, Edelman 2008).

5. Conclusions

Research on Artificial Neural Networks is still in progress. The evolution of this field, whose foundations were put by McCulloch and Pitts in 1943 (McCulloch, Pitts 1943) and, successively, were carried out by Rosenblatt (1958), Minsky (Minsky, Papert 1969), Rumelhart, Hinton and Williams (Rumelhart *et al.* 1986), was characterised in the last 20 years by explorations towards new ways of conceiving neural networks in terms of connectionist structures, training algorithms, neuron modelling and modern technologies for a physical implementation and usage. Nevertheless, several theoretical aspects have not been still sufficiently analysed and the future of neural networks field will certainly be characterised by the following aspects:

1) ANNs are basically an attempt to model the cortical neural circuits involved in natural cognitive processing. Up to now, a general theory about the development of cognitive functions in Artificial Neural Networks has not yet been formulated, even if several theoretical approaches to artificially emulate some fundamental brain cortex areas (as sensorimotor cortex, primary visual and auditory cortex) were proposed by means of classical artificial structures (Farkaš, Miikkulainen 1999; Boes *et al.* 2012; Adams *et al.* 2013). In this

framework, the involvement of Darwinist approaches, by means of Genetic Algorithms whose genetic information is related to the network structure, allows once more to select suitable neural networks aimed to cognitive tasks.
2) One of the most significant criticisms levelled to classical approaches to ANNs is the so-called Plasticity-Stability Dilemma. All the common training algorithms used to set the synaptic weights in an ANN work in a preliminary (off-line) stage whose finality is only to find the best configuration for the successive usage of the network. During the normal functioning of the ANN, adding some new training data is not recommended since a further training phase which does not take into account the old already trained information could lead to a total substitution of the stored information and the deletion of the original information. Grossberg (1987) tried to address this issue by proposing a particular neural processing called Adaptive-Resonance Theory (ART), inspired to some neurobiological evidence, allowing the coexistence of the two phases and avoiding the destruction of the information already learned. However, ART cannot be extended to the other well-defined ANNs as Perceptron or SOM, and some other heuristic approach is required to address such a specific problem.
3) Some more philosophical issues involved the world of ANNs, with particular reference to one of the most discussed topics of the Artificial Intelligence and the connection between brain and mind. Some authors (Penrose 1989) proposed to address the issue with a reductionist approach, theorising a more complex functioning of individual neurons whose neurobiological mechanisms are affected even by a quantum level. Since the molecular action plays a fundamental role in the neuronal dynamics, the neuron modelling should take into account the quantic nature of such mechanisms in order to build a solid general theory leading to uncover the still mysterious relations between biological matter and conscience.

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ABSTRACT

Understanding the world around us is usually a hard task. All dynamically evolving phenomena in the natural world are produced by a strong interaction among a great number of causes and, often, only a few amounts of them are visible or measurable. Moreover, the phenomena may be so widely distributed over space and time, like the weather evolution, that only a small number of measurements can be taken, making the understanding of the overall system difficult and approximated. Some characteristics of systems can produce a very strange behaviour, even when the elements constituting the system are a small number. All these elements and their mutual interaction can produce the so-called complexity. Artificial Neural Networks (ANNs) form an interesting class of dynamic systems, as a paradigm of natural and spontaneous computation. ANNs are founded on bases inspired by the neurophysiological nature of neurons and their mutual connectivity. In this paper the historical reasons that led to the former mathematical models of neuron and connectionist topologies will be detailed. Over time, they have evolved through the feed-forward systems, Self-Organizing Maps, the associative memories up to the latest models in artificial cerebral cortex.

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ANNs AND GEOGRAPHICAL INFORMATION FOR URBAN ANALYSIS EVIDENCE FROM THE EUROPEAN FP7 SECOA PROJECT

1. Introduction

The need to collect and compare data so that social scientists could study urban development began to be addressed in the 1960s, when UNESCO set up the ISSC (International Social Science Council) to interpret increasingly global urban phenomena and satisfy the need to identify models capable of describing the evolution of these phenomena. The advantages and disadvantages of comparative analysis with regard to the quantity and quality of available data were taken into consideration from the outset (Montanari 2012a). While the natural sciences have similar problems, the methods used do not require total comparability so much as repeated tests using the same procedures, and possibly the same approach (Montanari 2012b). The need to identify a shared interpretive model for all the world's cities derives from the fact that the economic and cultural impetus behind the growth of these cities has a common matrix, which is stimulated by communication and information exchange. In Calvino's poetic interpretation (Calvino 1972), every city derives from a common model. This general model contains all the standard features of a city; as a good public administrator, Kublai Khan, who is conversing with Calvino's fictitious Marco Polo, must take the model into consideration and envisage necessary exceptions to the rule, calculating the most probable as well as the most convenient combinations.

The writer Calvino's theory (Calvino 1974) was used as a reference point by the geographer Berry (1976), in marked contrast to the position adopted at the time by the International Geographical Union (IGU) regarding the fundamental differences between countries with free market and planned economies (Montanari 2012a). The existence of a common reference model has been confirmed by a number of studies over the past few decades. Cities will continue to grow, and to spread the impact of the changes they are undergoing to the surrounding territories in a number of different ways that, however, always derive from a shared model. Therefore, identifying a benchmark urban model – however complex the task – must continue to be the objective of research so as to understand processes, create a framework for policy intervention and anticipate possible future scenarios. Traditional inference methods were generally used to construct these models. This was possible as long as there was a relatively small quantity of data. In recent decades, however, new variables have been added to the earlier ones to correlate environmental changes with economic and social development as well as the significant amount of geographic data generated by contemporary society. From the 1992 Rio de Janeiro conference onwards, it was agreed that all countries would take environmental concerns into account for all human activity. This principle has gradually become entrenched within the fields of analysis, programming and research. In Europe, Framework Programme 7 (FP7, 2007-2013) has made it a factor in all EU-funded research projects. The new requirements that emerged as a result of the 1992 conference include that of dissemination, i.e. the need to communicate the results of complex computational procedures to the various categories of stakeholders that make up civil society.

This article looks at two elements of geographic analysis applied to urban processes: GISystems, software for analyzing geographic information, and GIScience, theories and methods to interpret geographic information. Self-Organizing Maps (SOM) are a type of Artificial Neural Network (ANN), initially studied by Kohonen, Hynninen, Kangas and Laaksonen (Kohonen *et al.* 1995), capable of automatically organising data within an artificial space in such a way as to group together data with similar characteristics while distancing dissimilar data. They are therefore able to preserve the topological relationships of archived data and produce output maps that can be analysed using a GISystem.

Because the "Solutions for environmental contrasts in coastal areas. Global Change, human mobility and sustainable urban development" project (SECOA) used data originated from the experiences of the natural and social sciences, the data collection and processing stages were complex. Complexity is characteristic of our society and, to explain phenomena related to us, it is increasingly necessary to analyse all the available data, whatever their origin: if these phenomena exist, they are relevant in one way or another to the formation of reality. So they must be identified and measured using the expedients that make it possible to subsequently include them in the rest of the information. SECOA considered two levels of phenomena: global ones such as climate change and human mobility, and local ones that emerge in the form of conflicts, the dynamics of urban growth, and natural, environmental, social and economic characteristics at the local level. The local is reliant on the global in that it is the positive or negative result of decisions taken and policies applied at a higher level. But the local level also concentrates all the consequences of improper management at the global level while contributing, through its errors and positive behaviours, to changes at the global level.

2. Methodological reflections

2.1 *From data to knowledge*

The results of the bibliographical research (Viaggiu 2013, 56-76) imply that up until the first ten days of the year 2000, little work had been done on the application of SOMs to GISs. Indeed, if we consider the articles published in scientific journals over the last thirty years, it is clear that twenty per cent of these publications concerned theories and models, ten per cent concerned urban analysis, and almost as many GIS and spatial analysis applications, while fifty per cent of the articles deal with medicinal applications. Moreover, around ninety per cent of this work has been published within the last ten years (Montanari 2013).

Skupin and Agarval (2008) remind us that in order to better understand the phenomena behind economic development and degradation of the environment, it has been necessary to produce a large quantity of geographical data. This process has further accelerated in recent years, during a period of economic crisis and climate change that has led to a reciprocal cause and effect situation in the local-global relationship. At a local level, the geographical data immediately showed, and continue to develop, a quantitative acceleration, the size of the pixels, as well as a qualitative acceleration, thanks to the use of satellites and GPS. At the same time, this further global-local relationship allowed refinement of the quality of the data at the local level, and greater comparability at the global level. This volume of data changed the methods of analysis and interpretation. Lacayo (2011) holds that the current volume of available data makes impossible to organise them by traditional methods, since the type of information that is necessary for knowledge of the phenomena is held in databases that can exceed hundreds of terabytes. The great potential for knowledge represented by the further increase in the quantity of data available remains bound by the fact that knowledge is ever more difficult to reach in relation to the complexity of the data. Ackoff (1989), and later Bellinger, Durval and Mills (Bellinger *et al.* 2004), and Bernstein (2009), developed a series of theories known by the term Data, Information, Knowledge, Wisdom (DIKW), for moving from the data-gathering stage to the information and then knowledge phases.

The practice of gathering and then processing data in what has become known as the Internet age has found further application and development in research into Data Mining (DM) and geographical knowledge (Giannotti, Pedreschi 2007; Buscema 2013), and on the subject of file sharing (Aigrain 2012). Berry and Linoff (1997) define data mining as the process of exploration and analysis of large quantities of data, with the end goal of identifying the hidden correlations between the pieces of information and making them visible. Alongside data mining, we should also remember the processes of Business Intelligence (BI), a term that indicates a series of processes for gathering and analyzing strategic information, the technology used to implement these processes, and the information they draw out. The relationship between data mining and statistical tools is constituted by their aptitude to a learning process that takes the data as a reference in order to convert them into information. Skupin and Agarval (2008) consider that in a situation with numerous data and complex phenomena, traditional methods of inference are ineffective or even constitute an obstacle to interpretation of the geographical entities, their relationships and meaning. Specifically, statistical analysis found an application in the field of spatial autocorrelation and in solving some problems linked to the traditional approaches. The use of computer-aided processes such as DM and knowledge discovery in databases (KDD) represented a solution that was not decisive. Lacayo (2011) proposed using GISystems as spatio-temporal and non-spatio-temporal components, turning them into pseudo-spatio-temporal components with SOMs.

2.2 *Knowledge and geographical information*

Skupin and Agarval (2008), in order to better position the relationships between SOMs and GIScience, consider it necessary to differentiate between supervised and unsupervised neural networks, and between feed-forward and recurrent ones. The type of SOM they took into consideration is one they consider traditional, used in clustering and display, presupposing an ANN type with competitive learning and no hidden layers (Londei 2013a).

The relationship between SOM and GIScience has occurred above all in one direction, the latter using the former for analytical purposes, with the reverse occurring relatively rarely. Lacayo (2011) points out that after the work of Kohonen, Hynninen, Kangas and Laaksonen (Kohonen *et al.* 1995) and the presentation of Li (1998), developments in the combined use of SOMs and GISystems were limited despite the separate progress made in the two methods. With Skupin and Agarval's volume, a new phase was opened in the use of SOMs and the possibility of them interacting with GIScience. Bação, Lobo and Painho (Bação *et al.* 2008), faced with the presence of large quantities of available data, introduced the need to reduce their number to quantitative and qualitative dimensions which are able to contribute to knowledge of the phenomena.

Lacayo (2011) also spent time on the difficulty of moving from data to information and from information to knowledge. Data are the primary and specific values of each object, while information is their structural form, which responds to questions such as who, what, when, where, and how many? The answer to these questions allows further information to be acquired and therefore knowledge of the phenomena.

Skupin and Agarval posed the problem of how SOMs can be adapted to the needs and paradigms of GIScience. Numerous researchers have tried to contribute to the creation of an industrial product, but this has not been fully realized yet and therefore it is still necessary to continue research in order to try to adapt SOMs to the needs and functionalities of GIScience. In many scientific fields, classification of objects is based on the similarity of their attributes. In GIScience, the concept of similarity considers both the "attribute space" parameter and geographical space, and the concept of similarity therefore assumes the value of proximity.

2.3 *Data values and their geographical representation*

Goodchild (2008), who introduced the concept of GIScience around twenty years ago (Goodchild 1992), notes that the SOM algorithm describes objects which are not necessarily located in the geographical space and makes no reference to their location. On the contrary, GIScience starts with the assumption that all objects are georeferenced. For this reason, the worlds of SOM and GIScience researchers have had few interests in common, and therefore little contact. Bação, Lobo and Painho (Bação *et al.* 2008) propose incorporating the First Law of Geography (FLG) into the SOM system so as to check for a possible balance between geographical proximity and the proximity of the values of attributes (Tobler 1970). The FLG is based on the concept that each variable is connected to all others, but those referring to phenomena which are close together are much more so than those which are distant. Some have criticised the FLG inasmuch as it appears to be a simplistic interpretation of geography in a situation which seems much more complex than can be explained by the simple relationships established between objects which are close together. In particular, it would seem impossible to explain complex ecological and socio-economic situations simply by looking at the spatial relationships established between the different entities. Despite these observations, the FLG is a reference for many scholars of geography and the social sciences, who consider it useful and satisfactory for their research. From a general point of view, the FLG distinguishes geography from the other disciplines as it assigns a specific and relevant meaning to the spatial component. Certainly the FLG cannot be considered in and of itself an exhaustive concept, but on the basis of this principle it is possible to extrapolate geo-spatial interpretation systems to better understand the present and anticipate what may happen in the future. Longley, Goodchild, Maguire and Rhind (Longley *et al.* 2005) assert that it is impossible to imagine that two maps of the same area, even though they may illustrate different phenomena, do not reveal some kind of similarity.

They therefore conclude with the assertion, based on numerous methods of statistical inference, that a spatial autocorrelation equal to zero is in contradiction with what seems evident based on the TFL. Complex Adaptive Systems (CAS) theory suggests that proximity may be a sufficient parameter. This happens because the interactions that occur at the local level, while simple, can contribute to the formation of global behaviors, often much more complex, which are not completely predictable or manageable. Montello, Fabrikant, Ruocco and Middleton (Montello *et al.* 2003) introduced the concept of displaying the semantic content of non-spatial information, such as documents in libraries. The principle of spatialisation is based on the "distance-similarity" metaphor. On the basis of the FLG, it is distance that determines similarity. The metaphor is based on assumptions analogous to the FLG, but arrives at opposing conclusions in that it is similarity that determines the distance in spatialisation, and this principle was named the First Law of Cognitive Geography (FLCG). The FLCG is based on empirical research in which the participants evaluated the similarity between documents depicted as points in spatialised displays. Further inspiration into the use of SOMs in GIScience came from the work of Tobler and Wineberg (1971), which referred to the use of cuneiform tablets to identify the location of the ancient urban settlements in Cappadocia. This analysis was performed on the basis of the number of tablets found in a settlement, which referred to other settlements.

The authors expressed their conviction that mathematical models based on contemporary urban structures have a temporally and geographically invariant structure and could therefore be used for Cappadocia. The research did not make reference to roads that existed at the time, only to the distance between the settlements. It was therefore then possible, solely on the basis of the distance, to identify the relative position and thereby hypothesise the geographical co-ordinates of the settlements to identify.

Tobler (2004), on the basis of observations and criticism of his work, explains that in the case of Cappadocia, the spatial gravity model was overturned to identify the missing settlements. Or, additionally, that spatial autocorrelation does not always have to be positive, as is evident from the effects of NIMBYism (Not in My Back Yard) in contemporary society.

2.4 *Geography and ANNs*

Bação, Lobo and Painho (Bação *et al.* 2004), starting from the assumption that one of the objectives of spatial research is the construction of uniform and homogeneous regions, considered the possibility of creating a Geo-Self-Organizing Map (Geo-SOM). Geo-SOM constitutes a tool to identify homogeneous regions for which it is possible to perform predictive analyses using tools that allow positive and negative correlations to be displayed. Bação, Lobo and Painho warn that in many scientific fields, classification is aimed at grouping different entities based purely on the notion of similarity of their attributes. In GIScience, classification is a compromise between the similarity understood as "attribute science" and that which identifies the "proximity" of the geographical space. An example of this theory is the application of Geo-SOM to the data from the 2001 Portugal census, composed of 70 attributes for 250 counties, categorised in relation to the number of inhabitants. Kropp and Schellnhuber (2008), on the other hand, used SOMs to examine the relationship between climate, soil type and global distribution of vegetation. In their case, the SOMs were used to analyse a large, multidimensional database using an algorithm that provides quantitative measurements for the topological ordering (SOMTOP model). When the data analysed are also georeferenced, it is then also possible to create maps with the classes indicated. Skupin and Hagelman (2005) relate the processing of the socio-economic variables for all of the 254 county units in Texas for the years 1980, 1990 and 2000.

A method is proposed for the spatialisation of the multitemporal and multidimensional trajectories using SOMs and GISs to represent them. The experiment provided good results, although the difficulty of integrating the corresponding software components remains, which the authors described as "loose coupling of SOM and GIS components". Fincke, Lobo and Bação (Fincke *et al.* 2008) explained the function of the SOM algorithm to present a number of frequently used display techniques. They also showed a method for importing the data processed with SOMs into a GIS environment, so that operations intended for spatial analysis may be applied to data which are originally non-spatial. Yi-Chen Wang and Chen-Chieh Feng (2011) report research performed on around 700 articles published between 1987 and 2007 in seven specialist publications concerning "land use/ cover change" (LUCC). The analysis of these papers was performed with SOMs whose results were then presented in visual form in order to contribute to better understanding of LUCC research activities. Li and Shanmuganathan (2007) applied a "social area analysis" model to Beppu City, a town in Japan. The authors noted that this type of analysis, particularly frequent in the preceding decades, has been performed little recently, for two main reasons: (i) The excessive simplification of the complexity of the residential urban structure, particularly through the use of linear correlation methods which often gave trivial results and (ii) The large quantity of work necessary to view the spatial characteristics of the phenomena. Combined use of SOMs and GISs allowed socio-spatial divisions in Japan to be identified as being above all in relation to age, or more precisely to the different periods in the life of each individual. Beppu City was therefore identified as being divided into two macro-areas, in turn divided into 6 and 2 sub-areas, for a total of 8 social areas.

Goodchild (2008) holds that SOMs do not consist of a trivial complement to the spatial analytic toolbox, but rather constitute a new paradigm for Exploratory Spatial Data Analysis (ESDA) and for spatial data mining. The ever-increasing use of SOMs and the good results this method provides poses major questions of GIScience in general and of its research agenda. At the same time, it is a positive signal for the writers of GIS software, in that they will have to consider the need to create a stand-alone toolbox rather than simply integrating part of the GIS functionality.

2.5 *Modelling and GIS*

Beginning with the work published in the first years of the new millennium (Openshaw, Abrahart 2000; Batty 2005), elaboration of urban models has been influenced by the new processing abilities and increasingly widespread use of GIS by civil services. Diappi (2004) examined the theory of Multi-Agent modeling, which refers to: (i) The processing architectures deriving from the application of artificial intelligence; (ii) A system which is able to extract rules from data and therefore interpret macro-phenomena by turning the top-down system on its head and (iii) The interest in a description of phenomena on a micro-urban scale. The behaviour of individuals is no longer interpreted in isolation, but also as interaction between themselves and with the context in which they live and operate. Diappi, Buscema and Ottanà (Diappi *et al.* 2004) delved deeper into the study of interaction between social systems, economic systems and the environment, highlighting its complexity. This requires the use of new scientific analysis methods, like ANNs. Diappi, Buscema and Ottanà (Diappi *et al.* 1998) state that in ANNs the rules are defined *a posteriori* on the basis of the variables, problems and objectives, unlike the traditional approach which is based on rules defined *a priori* for general parameters providing for a top-down system. Torrens (2010) considers that in the current situation of data availability, the social sciences are required to use IT tools to recognise the forces driving change in economic and social systems. It is precisely the progress in our capacity to process information that has further grown the role of geography, a discipline which is able, by its very nature, to manage complexity.

But why has the need arisen to describe individuals' behaviour in their physical, economic and social environment with a model? According to van der Leeuw (2004), models are useful to describe, succinctly and precisely, that large dimension of relationships which would otherwise have to be described, in an approximative manner, with words. He considers this reflection in the area of multidisciplinary research. In this type of activity, each discipline is presented using its own parlance, while the model offers a tool which can be acceptable to all disciplines and at the same time able to acknowledge all contributions that the individual disciplines are able to provide. Diappi, Bolchi and Buscema (Diappi *et al.* 2004) highlight a further characteristic of ANNs, represented by the possibility of increasing knowledge of urban dynamics by multiplying the information capacities of GISs and therefore offering a new methodological approach to creating models.

3. Empirical evidence: the SECOA Project

3.1 *The European FP7 SECOA Project*

The SECOA Project (http://www.projectsecoa.eu/) funded by the European Commission as part of the FP7 programme (2009-2013) studied new human mobility flows, whether the production-led kind also known as economic migration, or consumption-led, such as mobility for purposes of tourism and leisure, which have grown as a result of urban and regional restructuring policies following the 1970s economic crisis. SECOA noted that the most problematic situations occur in coastal areas because of a more fragile environment, space constraints and more concentrated phenomena. The availability of cultural and natural resources being more limited in coastal areas, the competition to use them is more acute. Problems in these areas are

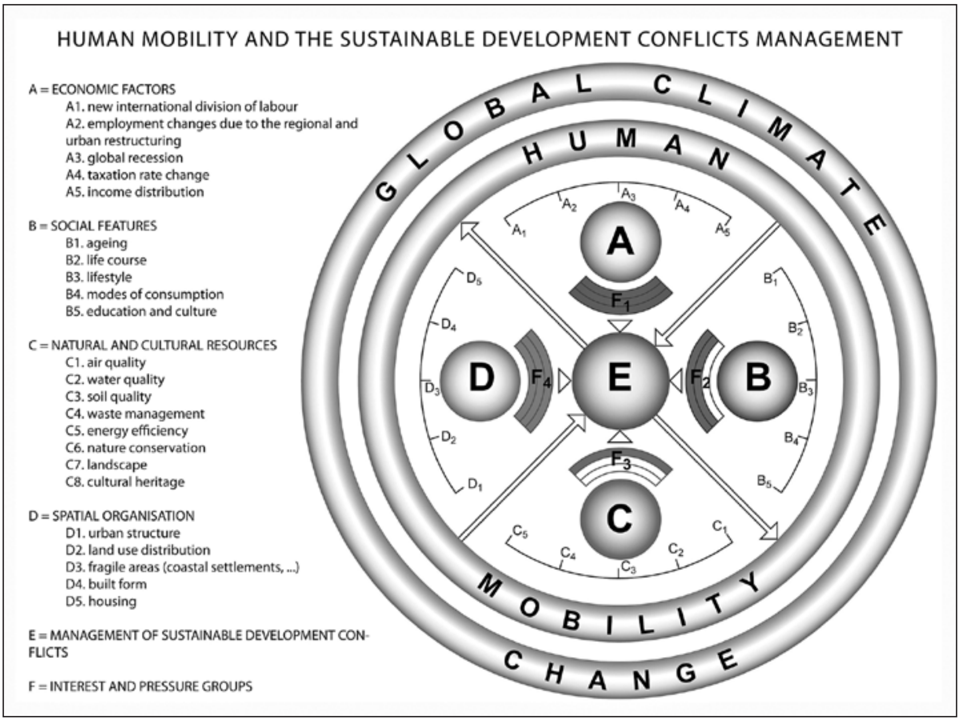

Fig. 1 – The SECOA methodological model: from global to local and vice versa.

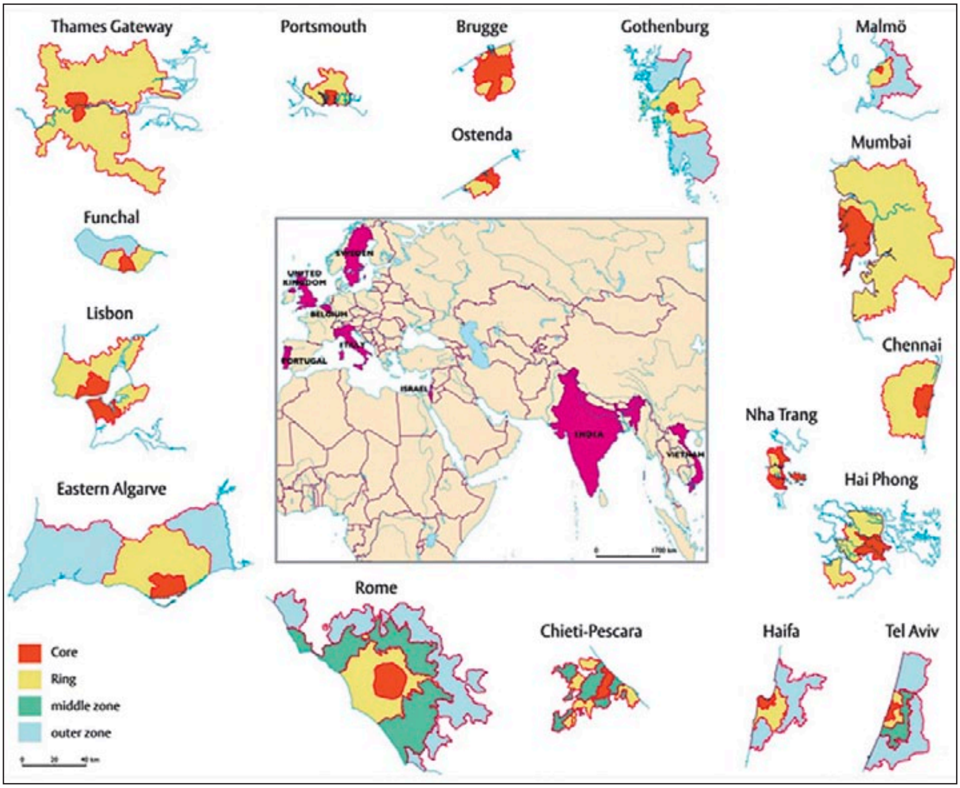

Fig. 2 – SECOA case studies.

intensified by global climate change, which enhances the risk of flooding and sea level rises in highly urbanised zones (Fig. 1).

Coastal areas are points where three elements – earth, sea and air – meet and interact, and therefore where the local encounters and clashes with the global, including from a physical standpoint. This particular situation is a prime observation point from which to view local-global environmental conflicts. SECOA identified these conflicts, analysed how they impact solutions to environmental problems, created interpretive models to summarise the quantitative and qualitative aspects of the conflicts in relation to the complexity of the environmental, economic and social systems, and compared the priorities of each type of conflict. The project examined eight coastal metropolitan areas of global significance and eight of regional significance in Europe and Asia (Fig. 2).

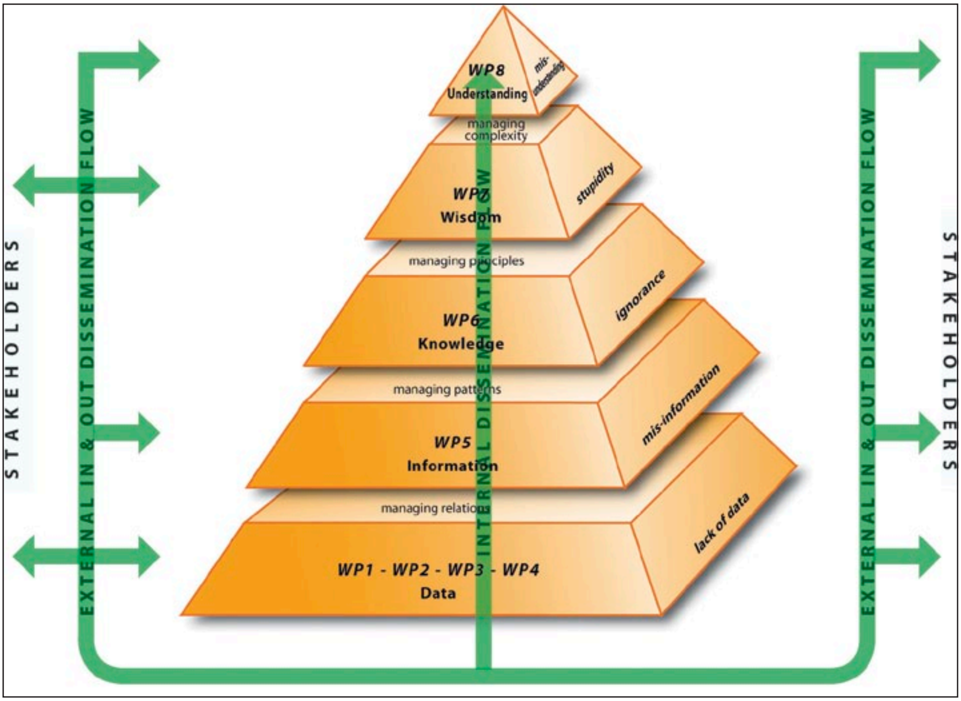

Fig. 3 – SECOA internal and external information pyramid. Source: adapted from Ackoff 1989; Bellinger *et al.* 2004

3.2 *From information to knowledge; SECOA's internal and external relations*

SECOA's logical path was based on two kinds of information. The first kind was applied within the project, with the objective of involving research groups that were not necessarily familiar with scientific collaboration (because of their culture and training) in a shared process. Despite the diversity of these groups and their dissimilar disciplinary approaches, the project had to include as many as possible of the fields that are familiar, at their individual level, with issues related to the development of coastal settlements.

There was also the need, explicitly requested in the European Commission's call for proposals, to include Pacific Rim countries. The second kind of information related to the various components of civil society that could serve, in each of the countries, to supply data, supervise the interpretation of data, carry out tests on the findings and be final users of the scientific findings (Fig. 3).

3.3 *Internal information and the continuity of the research activity*

SECOA's logical system for internal information was organised along the DIKW hierarchy model, with the meanings of each level of available information – totally comparable, only partly available, or missing and therefore comparable only after a series of qualitative interpretation processes – being entered into the model. The non-comparability of data when operating internationally was taken into account right from the design phase of the project proposal, and remained a constant throughout, as it is impossible to know in advance what data – because of cultural, social, economic and linguistic differences – will not be available, or only partially available, or available but relating to only superficially analogous phenomena. In fact, there can be different translations of the underlying meanings typical of each culture even when a common language is being used. A consistent information pyramid was obtained through the temporal and thematic organisation of SECOA into an operating sequence of eight work packages (WP). The information levels could therefore be matched to the objectives of the individual SECOA WPs, and to the comprehension and interpretation processes used to switch from one cognitive level to the next (Fig. 4).

The data to measure natural, environmental, social and economic phenomena were collected using different disciplinary and cognitive approaches; this was among the tasks of WP1-WP2-WP3-WP4. After being processed the data were collected, for WP1-WP2-WP3, in alphanumeric form, with numeric titles and values, and georeferenced form. WP4, for its part, classified conflicts using qualitative parameters, depending on how they were perceived by stakeholders in each of the areas studied. The subjects of the environmental conflicts taken into consideration were: (i) Projects for economic growth and plans to develop industry, ports and tourism; (ii) Protecting areas of environmental and cultural value and (iii) The changes that human mobility flows have brought about for the host society. These are conflicts that emerge because of environmental scarcity – as in the case of coastal areas – as a result of the over-utilisation of these areas due to their potential for economic development and ability to attract human mobility flows. Although the very nature of these conflicts makes them impossible to resolve, they can change and evolve, depending on the characteristics of each reference society, in more or less markedly different ways, despite the presence of common elements that are the result of cultural globalisation. The second level of the pyramid, WP5-WP6, required the creation of parameters capable of answering questions such as who, what, where and when. Knowledge includes the conscious use of data, and must be able to confirm the logical consistency of the research. The knowledge phase is the junction through which any research project, national or international, must pass. Without an appropriate rationale, and

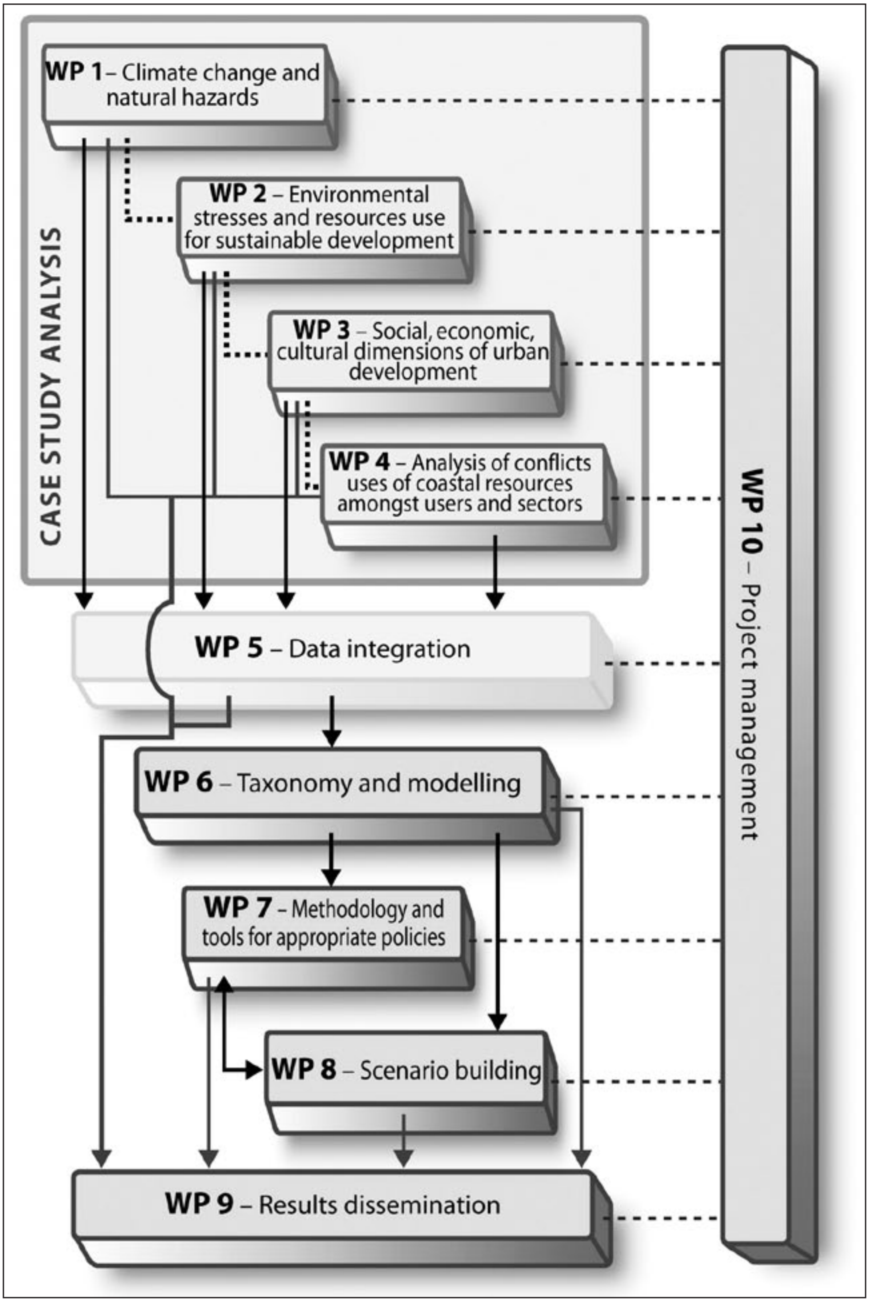

Fig. 4 – SECOA's work organisation and the information pyramid.

subsequent processing phase, data collection would be a banal process, and wholly unscientific: the question, after all, is how and why data is organised and can thereby offer added value.

The phase of discernment and wisdom – SECOA WP7 – drew up evaluation criteria for policies that can be applied on the basis of knowledge processes. Wisdom is particular to human beings; it presupposes an ability to reason with a soul, a heart and a mind. The SECOA WP8 stage of understanding phenomena was the final process in the project – a simultaneous stage of knowledge and analysis. A civil society that has correctly understood environmental conflicts in coastal areas is capable of taking the most appropriate initiatives because it is able to put the new knowledge it has acquired into practice. The knowledge in itself is not new; it is new because it results from an original way of processing known and published information.

3.4 *Communication and dissemination*

Fig. 4 also shows another level of information within the relationship between the various phases of the pyramid and civil society, represented by its stakeholders. These can be information flows that the project gathers through stakeholders; outgoing information flows – generally called dissemination – and flows that are both incoming and outgoing. Information that merely transmits the findings of scientific research to stakeholders cannot be defined as dissemination. This creates two problems for stakeholders: being relegated to a solely passive role, and not being fully aware of what data is being processed. For SECOA, dissemination was a process of mutual information-sharing rather than a one-way activity. At the data collection stage, in particular, stakeholders contributed to interpreting data and approving the way they were used by the research project.

In this way, the data were a means of communication, not merely a way for one side to dominate the other: one side gathers data using its own parameters, and the other interprets the data according to its culture and the purpose of its work (Montanari 2012a). In the knowledge phase, although stakeholders cannot take an active part in the research (which can occasionally be based on methods that might be considered abstruse), they can contribute to ensuring that data are correctly verified within the interpretive freedom of each part of the process. It was only at the apex phases of the pyramid that information was produced by research and then transmitted to the stakeholders, who then used it to adjust their policies and behaviours. The use of GISystems was a key dissemination tool at every stage, and with all the variables considered. Georeferenced data has an advantage over alphanumeric data: it can be subjected to a preliminary verification with the territory to which it has been assigned, and is more easily understood. Meanwhile, civil society too has acquired greater familiarity with the spread of GPS in most of the equipment used in everyday life.

3.5 *The descriptive model*

In the project planning phase, which also drew on existing literature and previous experience, the urban areas to be studied were divided into two categories: (i) Metropolitan areas of international significance that are being hugely impacted by global phenomena and (ii) Urban areas of regional significance that are impacted by global phenomena as experienced on a national scale. Including countries from within as well as from outside the EU enriched the research, but it also made comparing the data a more problematic affair. So the data were processed following these criteria:

1) All of the data collected for the research programme were used, even without a uniform level of comparability. When it came to data collection for SECOA WP1-WP3-WP3-WP4, the coordinators were specifically chosen for their skills in the environmental, economic or social fields, depending on the information required. Using ANNs made it possible to give data, not algorithms, the key role, thereby enhancing the ability of each individual piece of data to contribute to explaining phenomena. This process was chosen over the traditional one of first selecting an algorithm, then inserting the data required to make it work.
2) Rather than carry out a comparative analysis of each variable for each case study – which we might define the horizontal approach – the data for each country were pre-emptively verified using a longitudinal approach in order to identify coherence at the national level.
3) The data for all the urban areas were compared only after they had been processed and had expressed their specificity in the aggregate.
4) The variables of conflicts were considered together with all the other variables of the same urban area.
5) Therefore, conflicts were examined within their territory of relevance, in the place where they started and continue.
6) Each case study was considered within the context of the interaction of its environmental, economic and social issues, and only then were the various metropolitan and urban areas compared.

For the EU countries, it was possible to obtain georeferenced data for all the urban territories; this was not always possible in such detail for the other countries. It was therefore decided to use a GISystem raster with 1 km cells. As Fig. 5 shows, storing data within a GISystem dataset allowed for easier and more significant transfer to an SOM to organise and structure metropolitan areas into a sequence of qualitative parameters that were grouped by type. Further elaboration into a~~n~~ SOM of the SOMS made it possible to identify eight types of situations in the metropolitan areas used as case studies. The conflict data produced by SECOA WP4, on the other hand, were processed using another SOM, and resulted in the identification

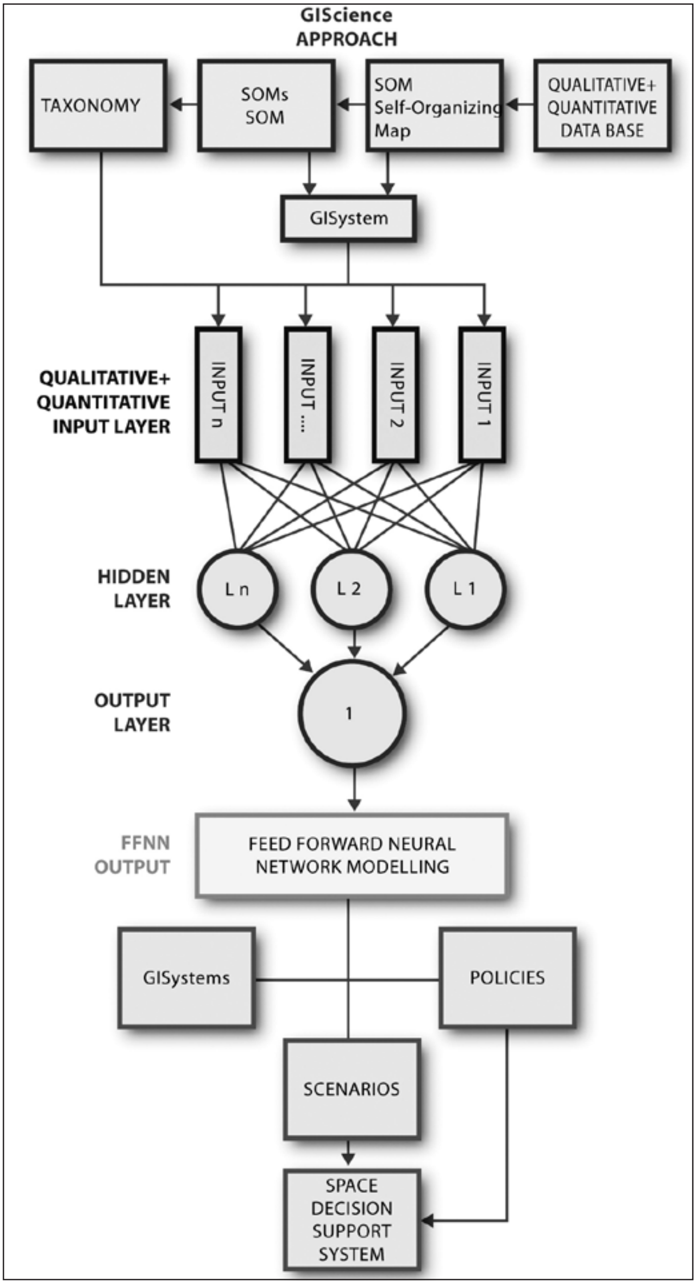

Fig. 5 – From environmental, economic and social variables to a descriptive model.

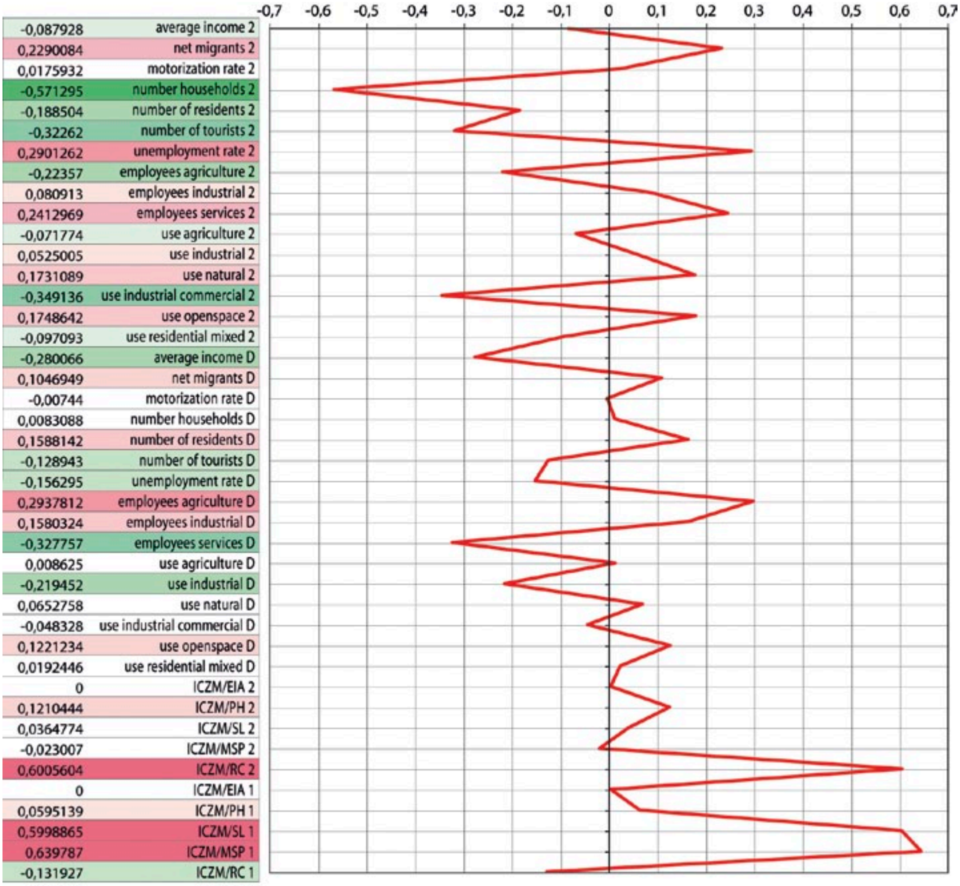

Fig. 6 – Descriptive model: the Civitavecchia (Rome) fingerprints. The variables marked in red indicate a positive trend. In this case, the generalised parameter of the conflict will tend to increase, thereby contributing to worsening its characteristics. The variables marked in green indicate a negative trend. In this case, the generalised parameter of the conflict will tend to decrease, contributing to its mitigation.

of five types of conflictual situations (Londei 2013b). As can be seen in Fig. 5, the SOMs and the SOM of SOMs were further elaborated using GISystems to make them easier for end-users and stakeholders to read and understand (Deravignone 2013). To proceed from the taxonomy to the interpretive model, a linear process was drawn up using a feed-forward neural network (FFNN).

The relevant areas of an environmental conflict in coastal areas vary from one case study to another. Even if the conflict is seemingly restricted to a small area – the place of intervention – there is also a larger area in which the characteristics of the conflict emerge and develop. SECOA identified three reference areas:

1) The direct area of the conflict – the place causing the conflict, where the environmental, economic and social variables are all 100 per cent relevant, and therefore contribute to understanding and describing the conflict.
2) The closest area to the conflict – the surroundings of the conflict area, including areas that are at least partially concerned by the reasons for the conflict. In this area, 20 per cent of the variables were deemed relevant. If the problem generating the conflict is industrial production, the areas affected by pollution from such production while simultaneously benefiting from it in economic terms are also taken into account.
3) The metropolitan area of the conflict: the wider area within which the conflict develops. Many problems in coastal areas emerge and develop inland – rivers contribute to flooding the coast when there is heavy rainfall, or lead to coastal erosion when river sand is overexploited. In this area, five per cent of the variables were considered to be relevant (Staniscia 2013).

An FFNN was built for each of the 17 case studies, with 52 output layers, 30 hidden layers, and descriptive modeling as the output: an identification code that supplied the greater or lesser importance in the emergence of the conflict of each of the 44 conflict themes and 52 social, economic and environmental variables taken into consideration.

This result was illustrated via a kind of vertical barcode providing the fingerprints of each case study (Fig. 6). Current or programmed policies that affect each variable either positively or negatively can contribute to increasing or reducing the intensity of the conflict.

4. Conclusions

SECOA has confirmed that environmental conflicts, like social conflicts, can never be entirely resolved. However, SECOA's interpretive model makes it possible to find tools to envisage ways to reduce the intensity of conflicts. Specifically, it has identified the variables that contribute most to conflict, and the intensity with which they contribute. Attentive policies can therefore work on particular components of the conflict to attempt to reduce their intensity. Research projects are increasingly multidisciplinary.

Contemporary society is increasingly developing along parameters of complexity, which require the use of research tools able to resolve problems related to large amounts of available data and the multiple relationships that have been established between them. The SECOA project's use of ANNs combined with GIS has demonstrated that it is possible to answer the following questions:

1) How do the environmental, economic and social variables interact? Are the characteristics of environmental conflict to be found among them?
2) How do these variables influence the characteristics of environmental conflicts?
3) How intense are these influences?
4) What variables are primarily responsible for the conflict?

Moreover, the use of ANNs together with GIS highlighted a series of advantages:

1) The option of using bottom-up methods that make it possible to be more closely connected to the issues to which the data point.
2) The enhanced flexibility of algorithms and models when it comes to the specific characteristics of individual data.
3) The field of geography has a natural tendency to connect seemingly disparate approaches, for which the territory can function as an instrument to help understand similarities in data.

By announcing upcoming calls for proposals for the Horizon 2020 research programme, the European Commission has, among other things, foreseen that, in order to meet to the needs of society, there will be greater call for multidisciplinary research capable of verifying subjects from different points of view. Moreover, public investment in research will have to envisage an immediate spillover to European society through increasingly sophisticated dissemination tools suited to the demand for knowledge. The geographical information provided by the ANN-GIS combination is undoubtedly in a position to contribute to this research.

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ABSTRACT

The Artificial Adaptive Systems (AAS) have had several applications in different technical and scientific fields, in medical research, life sciences, and financial and insurance studies. These systems have had, so far, poor implementation in social sciences. Among the latter, the main examples can be found in research about urban models in which AAS are usually used together with GISystems. By their nature, neural networks are suitable for interpreting complex phenomena like the social ones. Their limited use is, therefore, surprising. It is just to explain a complex phenomenon that AAS have been used in the SECOA project. The project deals with the study of environmental conflicts in coastal areas. Environmental conflicts are, by nature, complex phenomena, multidimensional and multiscalar. In SECOA 26 conflicts in 17 regions were analysed. The AAS were used to generate an explanatory model that would allow to describe, through its essential elements, the relationship between conflicts and territories. AAS are not only an ordinary complement to the spatial analysis toolbox but a new paradigm for spatial analysis and mining. In particular Geo-SOM (Geo-Self-Organizing Map) is a tool to identify homogenous regions for which predictive analysis can be done using tools that make the visualisation of positive and negative correlation possible. Increased use of AAS and GIS, and the good results this method produced, contributed to a more precise identification of a GIScience in general and its research agenda in particular.

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COMPUTER SCIENCE PROCEDURES FOR THE LABORATORY OF ANALYTICAL ARCHAEOLOGY AND ARTIFICIAL ADAPTIVE SYSTEMS (LAA&AAS)

1. Introduction. Data mining and Artificial Neural Networks

Data mining is a recently developed research field based on achievements of other disciplines, such as computer science, through research in machine learning, and statistics, through the development of multivariate and computational methods. The techniques of machine learning, in the context of the development of technologies within the field of artificial intelligence-related studies, aim at extracting from data relationships and patterns for the generation of a model of a phenomenon, which allows not only to reproduce the data generating process, but also to generalise what has been observed in relation to data not yet in our possession, to define decision support tools to formulate and validate hypotheses, to simulate scenarios of action. Data mining is an integrated set of analytical techniques, divided into various procedural steps ranging from modeling to exploration and features selection designed to extract unknown a priori knowledge from large datasets, apparently containing no regularity and important relationships

Data mining activity is not limited to the creation of query tools formulated through the SQL language or sophisticated data-retrieval tools aimed at providing multidimensional displays reports. If these tools allow to extract information from the database, the extraction process is strongly dependent on deductive research hypotheses formulated explicitly by the user. Moreover, this extraction is not inspired by modelling and synthesis provided by statistical methodology. In case the number of variables to be analysed simultaneously is high, tens or hundreds, the process of generating a hypothesis and the database analysis for the purpose of verification or falsification is no longer feasible. But data mining cannot be limited to the application of statistical methodology. Compared to the methods developed in machine learning, statistical methods suffer from the strong dependence on the data and a conceptual paradigm of reference. Although these factors have contributed to the definition of consistent and rigorous methods, they have limited the ability to quickly respond to requests advanced by methodological developments of information technology and the development of the applications of machine learning. Statisticians have initially disputed that in data mining there is not a unique theoretical model, but many competing models that are selected on the basis of test data. It follows that it would always be possible to find a model, although complex, which fits to the data. In addition, the abundance of data could lead to find non-existent relations. Although these considerations are valid, modern data mining methodologies aim to define procedures for model validation and thus for the estimate of its predictive capability, of its function as an effective decision support tool, as a tool for exploration of alternative hypotheses and possible scenarios, especially in the case where the large mass of data does not allow, by itself, to formulate a hypothesis or define a model. In this chapter we propose a graph-based data mining and an artificial neural network-based data mining.

Graphs become increasingly important in modeling complicated structures, such as circuits, images, biological networks, social networks, the Web. Many graphs search algorithms have been developed in chemical informatics, computer vision, video indexing and text retrieval. With the increasing demand on the analysis of large amounts of structured data, graph mining has become an active and important theme in data mining. Much of the data is structural in nature, or is composed of parts and relations between the parts, so a need exists to develop techniques to analyse and discover concepts in structural databases. We will propose a multidimensional data analysis based on a graph theoretic concept, called Minimum Spanning Tree. For many purposes a minimum spanning tree can capture the key essential information of a dataset. Multidimensional datasets can be represented as a minimum spanning tree without losing any essential information.

Three different Minimum Spanning Trees will be showed: in the first two cases, the metrics which defines trees properties are two well-known statistical measures, Linear Correlation and Prior Probability. The properties of the third tree are based on the innovative contribution of a new artificial neural network, the Auto Contractive Map (Auto-CM), designed by P.M. Buscema at the Semeion Research Center of Rome, Italy.

Auto-CM is an unsupervised network, a system that can learn to represent particular input patterns in a way that reflects the statistical structure of the overall collection of input patterns. By contrast with supervised learning or reinforcement learning, there are no explicit target outputs or environmental evaluations associated with each input. The goal of this kind of learning is to build representations of the input that can be used for decision making, predicting future inputs, efficiently communicating the inputs to another machine, etc. Unsupervised learning can be thought of as finding patterns in the data what would be considered pure unstructured noise. Two very simple classic examples of unsupervised learning are clustering and dimensionality reduction, the projection of input of M dimension in an output space with lesser dimension, maintaining topological properties of that input. After introducing the learning equations of Auto-CM networks, we will show a simple application through a well-known benchmark toy dataset, referring the reader to other chapters of the volume for applications within the ARCHEOSEMA project (Ramazzotti 2012, 2013).

2. Minimum Spanning Tree (MST)

A graph is a mathematical abstraction that is useful for solving many kinds of problems. Fundamentally, a graph consists of a set of vertices, and a set of edges, where an edge is an object that connects two vertices in the graph. More precisely, a graph is a pair (V, E), where V is a finite set and E is a binary relation on V, to which it is possible to associate scalar values defined by a specific metrics. V is called a vertex set whose elements are called vertices. E is a collection of edges, where an edge is a pair (u, v) with u, v belonging to V. In a directed graph, edges are ordered pairs, connecting a source vertex to a target vertex. In an undirected graph, edges are un-ordered pairs and connect the two vertices in both directions, hence in an undirected graph (u, v) and (v, u) are two ways of writing the same edge – Minimum Spanning Trees produced by research experimental software ARCHEOSEMA Lab (see Appendix) – are visualised and manipulated by the free open source software GEPHI v. 0.8.1, an interactive visualisation and exploration platform for all kinds of networks and complex systems, dynamic and hierarchical graphs (for information and tutorials visit: https://gephi.org/).

The graph-theoretic representation is not constrained by any a priori semantic restriction: it does not say what a vertex or edge actually represents. They could be cities with connecting roads, or web-pages with hyperlinks, and so on. These semantic details are irrelevant to determine the graph structure and properties; the only thing that matters is that a specific graph may be taken as a proper representation of the phenomenon under study, to justify attention on that particular mathematical object. An adjacency-matrix representation of a graph is a 2-dimensional VxV array, where rows represent the list of vertices and columns represent edges among vertices. To each element in the array is assigned a Boolean value saying whether the edge (u, v) is in the graph. A distance matrix among V vertices represents an undirected graph, where each vertex is linked with all the others but itself (Tab. 1):

	A	B	C	D	…	Z
A	0	1	1	1	1	1
B	1	0	1	1	1	1
C	1	1	0	1	1	1
D	1	1	1	0	1	1
..	1	1	1	1	0	1
Z	1	1	1	1	1	0

Tab. 1 – Adjacency matrix.

The Minimum Spanning Tree problem is defined as follows: find an acyclic subset T of E that connects all of the vertices in the graph and whose total weight (the total distance) is minimised, where the total weight is given by:

$$d(T) = \sum_{i=0}^{N-1} \sum_{j=j+1}^{N} d_{i,j} \quad \forall d_{i,j} \tag{1}$$

T is called a spanning tree, and the MST is the T whose weighted sum of edges attains the minimum value:

$$\mathrm{Mst} = \mathrm{Min}\{\mathrm{d}(\mathrm{T}_{\mathrm{k})}\} \tag{2}$$

Given an undirected graph G, representing a matrix of distances d, with V vertices, completely linked to each other, the total number of their edges (E) is:

$$E = \frac{V(V-1)}{2} \tag{3}$$

and the number of its possible spanning trees is:

$$T = V^{V-2} \tag{4}$$

The first algorithm for finding a minimum spanning tree was developed by Czech scientist Otakar Borůvka in 1926 (Borůvka 1926). Its purpose was an efficient electrical coverage of Moravia. There are now two algorithms commonly used, Prim's algorithm (Prim 1957) and Kruskal's algorithm (Kruskal 1956). All three are greedy algorithms, following the problem solving heuristic of making the locally optimal choice at each stage with the hope of finding a global optimum. In many problems, a greedy strategy does not in general produce an optimal solution, but nonetheless a greedy heuristic may yield locally optimal solutions that approximate a global optimal solution in a reasonable time. Obviously, the Kruskal algorithm generates one of the possible MSTs. In fact, in a weighted graph more than one MST is possible. Applications of MST include the design of various types of distribution networks in which the nodes represent cities, centers, etc.; and edges represent communication links (fiber glass phone lines, data transmission lines, cable TV lines, etc.), high voltage power transmission lines, natural gas or crude oil pipelines, water pipelines, highways, etc. The objective is to design a network that connects all the nodes using the minimum length of cable or pipe or other resource. The minimum cost spanning tree problem also appears as a sub-problem in algorithms for many routing problems such as the traveling salesman problem.

MST have long been used for data classification in the field of biology (States *et al.* 1993; Xu *et al.* 2001, 2002), for data classification in the field of image processing and pattern recognition (Duda, Hart 1973; Gonzales, Winz 2002; Ma *et al.* 2000) and in many other research fields (Devilliers, Dore 1989; Tapia, Rojas 2004; Assunção *et al.* 2006). A Minimum Spanning Tree is generally considered as a skeleton of a graph. For many purposes a minimum spanning tree can capture the key essential information of a graph.

Multidimensional dataset can be represented as a minimum spanning tree without losing any essential information for the purpose of clustering. From conceptual point of view, the MST represents the energy minimisation state of a structure. In fact, if we consider the atomic elements of a structure as vertices of a graph and the strength among them as the weight of each edge, linking a pair of vertices, the MST represents the minimum of energy needed so that all the elements of the structure preserve their mutual coherence. In a closed system, all the components tend to minimise the overall energy. So the MST, in specific situations, can represent the most probable state for the system to tend. To determine the MST of an undirected graph, each edge of the graph has to be weighted. So we need to define a way to weight each edge whose nodes are the entities of a dataset (records or variables).

3. Two base metrics: linear correlation and prior probability

It is possible to use any algorithm to weight the graph edges, although the final outcome will be in general quite different. It is therefore useful to review briefly some of the most used options in the current practice.

3.1 *Pearson's linear correlation*

First it is necessary to calculate the linear correlation between each pair of variables of the assigned dataset:

$$R_{i,j} = \frac{\sum_{k=1}^{N}(x_{i,k} - \bar{x}_i)\cdot(x_{j,k} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{N}(x_{i,k} - \bar{x}_i)^2 \cdot \sum_{k=1}^{N}(x_{j,k} - \bar{x}_j)^2}}; \tag{5}$$

$$-1 \le R_{i,j} \le 1; \qquad i, j \in [1, 2, ..., M]$$

where:

$R_{i,j}$ = linear correlation between any couple of variables x_i and x_j of the assigned dataset;

= mean value of any variable I, j;

N = number of records of the assigned dataset;
M = number of variables of the assigned dataset.

The equation (4) will generate a symmetric squared matrix with null diagonal, providing the linear correlation between each variable and any other. Through the following equation (5), the correlation matrix is transformed into a matrix of linear distances among the variables:

$$d_{i,j}^{[R]} = \sqrt{2 \cdot (1 - R_{i,j})} \tag{6}$$

At this point, following the same steps as above, the assigned dataset can be reformulated as an undirected weighted graph, where MST optimisation is applicable.

3.2 *Prior probability*

First we calculate the prior probability of co-occurrence between any couple of variables of the assigned dataset:

$$A_{i,j} = -\ln \frac{\frac{1}{N^2} \cdot \sum_{k=1}^{N} x_{i,k} \cdot (1 - x_{j,k}) \cdot \sum_{k=1}^{N} (1 - x_{i,k}) \cdot x_{j,k}}{\frac{1}{N^2} \cdot \sum_{k=1}^{N} x_{i,k} \cdot x_{j,k} \cdot \sum_{k=1}^{N} (1 - x_{i,k}) \cdot (1 - x_{j,k})} \tag{7}$$

$$-\infty \le A_{i,j} \le +\infty; \quad x \in [0,1]; \quad i, j \in [1, 2, \ldots, M]$$

where:

$A_{i,j}$ = Association strength between any couple of variables x_i and x_j of the assigned dataset;
x_i = value of any variable scaled between 0 and 1;
N = number of records of the assigned dataset;
M = number of variables of the assigned dataset.

The transformation of the matrix of association among variables into a non-linear distance matrix is generated by the following equation (8):

$$d_{i,j}^{[A]} = MaxA - A_{i,j} \tag{8}$$

where *MaxA* = Maximum *A* matrix value.

4. Advanced ANN metrics: Auto Contractive Map Network (Auto-CM)

All of the above options have the advantage to be very fast computationally, but their common, serious limit is to define the distance among variables or records by just picking them in couples. That means that each weight explains the association between two variables or records, but it does not take into account the additional influence that other variables or records could exert on that specific couple. This situation is quite similar, say, to the case of ten children playing all together in a swimming pool. If one would pretend to explain their global behaviour by making the statistics of the interaction between all possible pairs of children, this would amount to skip all of the external constraints that the concomitant positions and movements of the other children are imposing on each given couple at each given moment. By skipping this crucial information, the actual mutual behaviour of each couple will be poorly understood, and a fortiori this will also be the case for the global picture that is built through the aggregation of such partial two-by-two views.The Artificial Neural Network Auto-CM could represent the best choice to compute a complete and a non-linear matrix of weights among variables or among records of any assigned dataset.

Auto-CMs "spatialise" the correlation among datasets entities (record and variables) by constructing a suitable embedding space where a visually transparent and cognitively natural notion such as "closeness" among entities reflects accurately their associations. This "closeness" can be converted into a compelling graph-theoretic representation that picks all and only the relevant correlations and organises them into a coherent picture. Such representation is not actually constructed through some form of cumbersome aggregation of two-by-two associations between couples of entities, but rather by building a complex global picture of the whole pattern of variation (Buscema, Grossi 2007; Buscema *et al.* 2008a; Helgason *et al.* 2009; Buscema, Maurelli 2011). In recent years this technique has been applied in a number of medical settings like Alzheimer disease (Buscema *et al.* 2008b; Licastro *et al.* 2010a, 2010b), Down syndrome (Coppedè *et al.* 2010), gastro-oesophageal reflux disease (Buscema, Grossi 2008c), and myocardial infarction (Street *et al.* 2008) showing the added value of this approach in comparison with traditional statistical techniques. These techniques are novel and therefore not entirely understood so far in all of their properties and implications, and that further research is called for to explore them. But at the same time we are convinced that their actual performance in the context of well-defined, well understood problems provides an encouraging test to proceed in this direction. The Auto-CM is characterised by a three-layer architecture: an Input layer, where the signal is captured from the environment, a Hidden layer, where the signal is modulated inside the Auto-CM, and an Output layer, through which the Auto-CM feeds back upon the environment on the basis of the stimuli previously received and processed (Fig. 1). Each layer contains an equal number of N units, so that the whole Auto-CM is made of 3N units. The connections between the Input and the Hidden layers are mono-dedicated, whereas the ones between the Hidden and the Output layers are fully saturated, i.e. at maximum gradient. Therefore, given N units, the total number of the connections, Nc, is given by:

$Nc = N\,(N + 1)$.

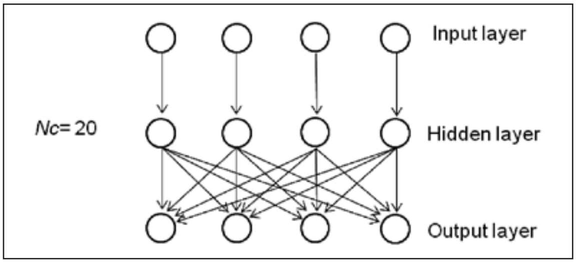

Fig. 1 – An example of an Auto-CM with N = 4.

All of the connections of Auto-CM may be initialised either by assigning a same, constant value to each, or by assigning values at random. The best practice is to initialise all the connections with a same, positive value, close to zero. The learning algorithm of Auto-CM may be summarised in a sequence of four characteristic steps:

1) Signal Transfer from the Input into the Hidden layer;
2) Adaptation of the values of the connections between the Input and the Hidden layers;
3) Signal Transfer from the Hidden into the Output layer;
4) Adaptation of the value of the connections between the Hidden and the Output layers.

We write as $m^{[s]}$ the units of the Input layer (sensors), scaled between 0 and 1; as $m^{[h]}$ the units of the Hidden layer, and as $m^{[t]}$ the units of the Output layer (system target). We moreover define **v**, the vector of mono-dedicated connections; **w**, the matrix of the connections between the Hidden and the Output layers; and n, the discrete time that spans the evolution of the Auto-CM weights, or, put another way, the number of cycles of processing, counting from zero and stepping up one unit at each completed round of computation.

In order to specify the steps 1-4 that define the Auto-CM algorithm, we have to define the corresponding signal forward-transfer equations and the learning equations, as follows:

1) Signal transfer from the Input to the Hidden layer:

$$m_{i_{(n)}}^{[h]} = m_i^{[s]} \cdot \left(1 - \frac{v_{i_{(n)}}}{C}\right) \tag{9}$$

where C is a positive real number not lower than 1, which we will refer to as the contraction parameter, and where the *(n)* subscript has been omitted from the notation of the input layer units, as these remain constant at every cycle of processing.

2) Adaptation of the connections through the variation, which amounts to trapping the energy difference generated according to equation (9):

$$\Delta v_{i_{(n)}} = (m_i^{[s]} - m_{i_{(n)}}^{[h]}) \cdot \left(1 - \frac{v_{i_{(n)}}}{C}\right) \tag{10}$$

$$v_{i_{(n+1)}} = v_{i_{(n)}} + \Delta v_{i_{(n)}} \tag{11}$$

3) Signal transfer from the Hidden to the Output layer:

$$Net_{i_{(n)}} = \sum_{j=1}^{N} m_{j_{(n)}}^{[h]} \cdot \left(1 - \frac{w_{i,j_{(n)}}}{C}\right) \tag{12}$$

$$m_{i_{(n)}}^{[t]} = m_{i_{(n)}}^{[h]} \cdot \left(1 - \frac{Net_{i_{(n)}}}{C}\right) \tag{13}$$

4) Adaptation of the connections through the variation, which amounts, accordingly, to trapping the energy difference as to equation (13):

$$\Delta w_{i,j_{(n)}} = (m_{i_{(n)}}^{[h]} - m_{i_{(n)}}^{[t]}) \cdot \left(1 - \frac{w_{i_{(n)}}}{C}\right) \cdot m_{j_{(n)}}^{[h]} \tag{14}$$

$$w_{i_{(n+1)}} = w_{i_{(n)}} + \Delta w_{i,j_{(n)}} \tag{15}$$

Even a cursory comparison of (9) and (13) and (10-11), (14-15), respectively, clearly shows how both steps of the signal transfer process are guided by the same (contraction) principle, and likewise for the two weight adaptation steps (for which we could speak of an energy entrapment principle). Notice how the term in (14) makes the change in the connection proportional to the quantity of energy liberated by node in favour of node. The whole learning process, which essentially consists of a progressive adjustment of the connections aimed at the global minimisation of energy, may be seen as a complex juxtaposition of phases of acceleration and deceleration of velocities of the learning signals (adaptations and) inside the ANN connection matrix (Buscema, Grossi 2007). There are a few important peculiarities of Auto-CMs with respect to more familiar classes of ANNs that need special attention and call for careful reflection:

1) Auto-CMs are able to learn also when starting from initialisations where all connections are set at the same value, i.e., they do not suffer the problem of the symmetric connections.
2) During the training process, Auto-CMs always assign positive values to connections. In other words, Auto-CMs do not allow for inhibitory relations among nodes, but only for different strengths of excitatory connections.

3) Auto-CMs can learn also in difficult conditions, namely, when the connections of the main diagonal of the second layer connection matrix are removed. In the context of this kind of learning process, Auto-CMs seem to reconstruct the relationship occurring between each couple of variables. Consequently, from an experimental point of view, it seems that the ranking of its connections matrix translates into the ranking of the joint probability of occurrence of each couple of variables.
4) Once the learning process has occurred, any input vector, belonging to the training set, will generate a null output vector. So, the energy minimisation of the training vectors is represented by a function by means of which the trained connections "absorb" completely the input training vectors. Thus, Auto-CM seems to learn how to transform itself in a "dark body"
5) At the end of the training phase the matrix **w**, then, represents the Auto-CM knowledge about the whole dataset.

For our purpose, the matrix **w** may be transformed into a non-Euclidean distance metric (semi-metric), when we train the Auto-CM with the main diagonal of the **w** matrix fixed at value N. Now, if we consider N as a limit value for all the weights of the w matrix, we can write:

$$d_{i,j} = N - w_{i,j} \tag{16}$$

The new matrix *d* is again a squared symmetric matrix, where the main diagonal entries are null (i.e., they represent the zero distance of each node from itself), and where the off-diagonal entries represent "distances" between each couple of nodes. Each distance between a pair of nodes may therefore be regarded as the weighted edge between these pair of nodes in a suitable graph-theoretic representation, so that the matrix *d* itself may be analysed through the graph theory.

5. Applications: gang toy dataset

5.1 *The dataset*

In this section we propose a validation of the tools discussed. The validation is based on a well-known benchmark introduced by McClelland and Rumelhart (1986, 1988), the *West Side Story* dataset where one has to distinguish members' affiliation in two rival gangs, the Jets and the Sharks, on the basis of certain numbers of identifying characteristics. This is a demanding benchmark in that characteristics are mixed up in a rather tricky way: Jets tend to be in their 20s, single and with a Junior High School education, although no one Jet member actually happens to meet all three criteria at the same time, whereas Sharks tend to be older, married and with a High School education, but again no one Shark happens to meet the three criteria simulta-

	Gang	Age	Education	Status	Profession
ART	Jet	40	Junior School	Single	Pusher
AL	Jet	30	Junior School	Married	Burglar
SAM	Jet	20	College	Single	Bookie
CLYDE	Jet	40	Junior School	Single	Pusher
MIKE	Jet	30	Junior School	Single	Pusher
JIM	Jet	20	Junior School	Divorced	Burglar
GREG	Jet	20	High School	Married	Pusher
JOHN	Jet	20	Junior School	Married	Burglar
DOUG	Jet	30	High School	Single	Bookie
LANCE	Jet	20	Junior School	Married	Burglar
GEORGE	Jet	20	Junior School	Divorced	Burglar
PETE	Jet	20	High School	Single	Bookie
FRED	Jet	20	High School	Single	Pusher
GENE	Jet	20	College	Single	Pusher
RALPH	Jet	30	Junior School	Single	Pusher
PHIL	Sharks	30	College	Married	Pusher
IKE	Sharks	30	Junior School	Single	Bookie
NICK	Sharks	30	High School	Single	Pusher
DON	Sharks	30	College	Married	Burglar
NED	Sharks	30	College	Married	Bookie
KARL	Sharks	40	High School	Married	Bookie
KEN	Sharks	20	High School	Single	Burglar
EARL	Sharks	40	High School	Married	Burglar
RICK	Sharks	30	High School	Divorced	Burglar
OL	Sharks	30	College	Married	Pusher
NEAL	Sharks	30	High School	Single	Bookie
DAVE	Sharks	30	High School	Divorced	Pusher

Tab. 2 – Gang dataset.

Item	Jets	Sharks	Jets(%)	Sharks(%)
20s	9	1	60.00	8.33
30s	4	9	26.67	75.00
40s	2	2	13.33	16.67
Junior School	9	1	60.00	8.33
High School	4	17	26.67	58.33
College	2	4	13.33	33.33
Single	9	4	60.00	33.33
Married	4	6	26.67	50.00
Divorced	2	2	13.33	16.67
Pusher	5	4	33.33	33.33
Bookie	5	4	33.33	33.33
Burglar	5	4	33.33	33.33

Tab. 3 – Gang dataset basic statistics.

neously. Moreover, all members of both gangs are equally likely to operate as pushers, bookies or burglars. We will see how the tools discussed in previous sections could provide an in-depth exploration of the structural properties of the dataset, then very useful information for a number of further tasks, including, for instance, analysis of clusters, scenario simulation and so on.

The Tab. 2 shows this dataset. The basic statistics is reported in Tab. 3.

5.2 Preprocessing

Each categorical variable (Gang, Age, Education, Status and Profession) is transformed using dummy variables: each item is transformed in a Boolean value, 1 or 0. This choice is particularly effective when the output is a graph or a neural network based on activations of nodes/entities. Tab. 4 shows the transformed dataset.

	Jet	Sharks	20	30	40	JH	COL	HS	Sing	Marr	Div	Push	Book	Burg
ART	1	0	0	0	1	1	0	0	1	0	0	1	0	0
AL	1	0	0	1	0	1	0	0	0	1	0	0	0	1
SAM	1	0	1	0	0	0	1	0	1	0	0	0	1	0
CLYDE	1	0	0	0	1	1	0	0	1	0	0	0	1	0
MIKE	1	0	0	1	0	1	0	0	1	0	0	0	1	0
JIM	1	0	1	0	0	1	0	0	0	0	1	0	0	1
GREG	1	0	1	0	0	0	0	1	0	1	0	1	0	0
JOHN	1	0	1	0	0	1	0	0	0	1	0	0	0	1
DOUG	1	0	0	1	0	0	0	1	1	0	0	0	1	0
LANCE	1	0	1	0	0	1	0	0	0	1	0	0	0	1
GEORGE	1	0	1	0	0	1	0	0	0	0	1	0	0	1
PETE	1	0	1	0	0	0	0	1	1	0	0	0	1	0
FRED	1	0	1	0	0	0	0	1	1	0	0	1	0	0
GENE	1	0	1	0	0	0	1	0	1	0	0	1	0	0
RALPH	1	0	0	1	0	1	0	0	1	0	0	1	0	0
PHIL	0	1	0	1	0	0	1	0	0	1	0	1	0	0
IKE	0	1	0	1	0	1	0	0	1	0	0	0	1	0
NICK	0	1	0	1	0	0	0	1	1	0	0	1	0	0
DON	0	1	0	1	0	0	1	0	0	1	0	0	0	1
NED	0	1	0	1	0	0	1	0	0	1	0	0	1	0
KARL	0	1	0	0	1	0	0	1	0	1	0	0	1	0
KEN	0	1	1	0	0	0	0	1	1	0	0	0	0	1
EARL	0	1	0	0	1	0	0	1	0	1	0	0	0	1
RICK	0	1	0	1	0	0	0	1	0	0	1	0	0	1
OL	0	1	0	1	0	0	1	0	0	1	0	1	0	0
NEAL	0	1	0	1	0	0	0	1	1	0	0	0	1	0
DAVE	0	1	0	1	0	0	0	1	0	0	1	1	0	0

Tab. 4 – Gang dataset preprocessed.

5.3 *Minimum Spanning Trees*

In this section we show the MST outputs based on the Auto-CM metrics. The Auto-CM weights matrix was calculated by the research experimental software *ARCHEOSEMA Lab* (see Appendix A).

The MST output file is a *.graphml type file and was visualised with the open source software GEPHI v. 0.8.1. We propose two types of trees, each based on different input of the artificial neural network Auto-CM:

1) Variables Tree: input corresponding to the matrix of Tab. 4. Nodes represent variables.
2) Records Tree: the input is transposed matrix of Tab. 4. Nodes represent records. Our trees analysis is based on three specific statistics measures that maintain their meaning even MSTs are acyclic graphs:
3) *Betweenness centrality*. It is a centrality measure of a vertex within a graph and quantifies the number of times a node acts as a bridge along the

shortest path between two other nodes. It was introduced as a measure for quantifying the control of a human on the communication between other humans in a social network by Linton Freeman. In his conception, vertices that have a high probability to occur on a randomly chosen shortest path between two randomly chosen vertices have a high betweenness (Freeman 1977). Betweenness centrality is a more useful measure of the load placed on the given node in the network as well as the node's importance to the network than just connectivity. The latter is only a local effect while the former is more global to the network. In a weighted network the links connecting the nodes are no longer treated as binary interactions, but are weighted in proportion to their capacity, influence, frequency, etc., which adds another dimension of heterogeneity within the network beyond the topological effects.
4) *Mean Weighted Degree of Nodes*: the mean weight of connections per node on the graph.
5) *Modularity*. It is one measure of the structure of networks or graphs. It was designed to measure the strength of division of a network into clusters. Networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules. Modularity is the fraction of the edges that fall within the given groups minus the expected such fraction if edges were distributed at random. The value of the modularity lies in the range [–1/2, 1). It is positive if the number of edges within groups exceeds the number expected on the basis of chance. For a given division of the network's vertices into some modules, modularity reflects the concentration of nodes within modules compared with random distribution of links between all nodes regardless of modules. The resolution coefficient is the main parameter to be set: a value higher than 1.0 (default) provides a minor number of clusters and then bigger ones (Newman 2006, 2007; Reichardt, Bornholdt 2006).

5.4 *Variables MST*

Fig. 2 shows the variables Minimum Spanning Tree. Values of connections between nodes correspond to the values of Auto-CM connections matrix and their thickness is proportional to the value of the connection. We can note the following:

1) *the separation between the two classes*, *Jets and Sharks*, *is clear*; the connections with the class nodes indicate to some extent the prototype of the classes themselves. If we compare the tree with data of Tab. 3, we can see that Age is one of the attributes that most distinguishes the two classes: one Shark is a thirty year old subject with a probability of 70%, while a Jet is twenties with a probability of 60% (note the maximum value of connections in both cases). Similarly, it is more likely that a Shark subject attends the High School, as well as a Jet subject attends the Junior School. Furthermore, a Jet

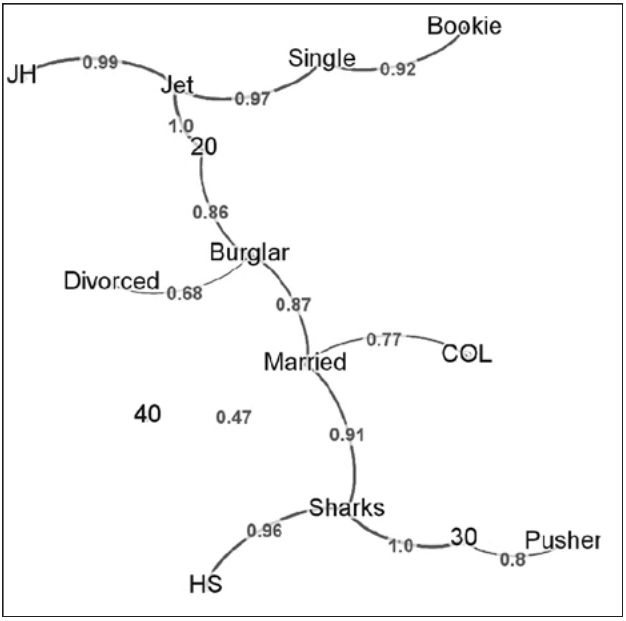

Fig. 2 – Gang variables MST.

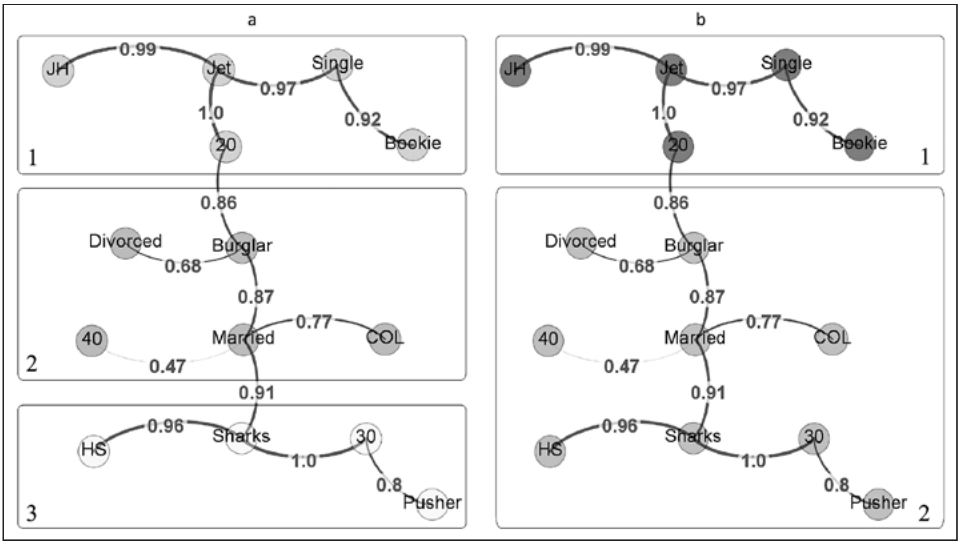

Fig. 3 – Gang variables MST: a) Resolution coefficient = 1; b) Resolution coefficient = 3.

subject is likely to be Single, while the fact that a Shark subject is Married is less likely, as this can be inferred from the fact that the node Married is linked to the node Sharks in a different way compared to the link between Jet and Single: it is in fact also connected to other nodes and can be regarded as a "transition" attribute between two classes;
2) the value of the connection between nodes 40 and Married is very low. In fact in the dataset there are 40 year old subjects who are both Single and Married, so this feature is not discriminating. However, the position of node 40 indicates that this attribute is typically a Sharks attribute. This idea could be deduced also from the distance, in terms of the sum of the linking connections values, of this node from two classes: 40-Sharks = 1,38, 40-Jet = 3.2;
3) the position of the node College points that this attribute is not discriminating as the attributes Age and Education. However, the College-Married connection is typically Sharks.
4) the Bookie attribute is typically Sharks, as a Bookie is typically a Single and this attribute, as already mentioned, is typically Shark.
5) the attribute Burglar is not discriminating. We find this feature in the tree, as a transition node between the two classes. From the dataset we can see that it is more likely that a Burglar is Married and that Divorced is a Burglar. In addition, the meaning of Burglar node as transition attribute is confirmed by its distances from nodes of the classes: Burglar-Jet = 1.86 while Burglar-Sharks = 1.78.

From this first analysis, we can conclude that this Minimum Spanning Tree has not only shown in a compact manner and immediately some relationships that were already inherent in the dataset, but it also has proposed not immediately noticeable solutions, available only through data manipulations. If these manipulations pose no relevant problem when working with small dataset, this feature of the MST based on matrix of connections Auto-CM becomes more relevant when working with dataset of more significant size. Fig. 3 shows GEPHI v. 0.8.1 clustering based on modularity resolution coefficient = 1 and modularity resolution coefficient = 3. Fig. 4 shows the nodes weighted degree statistics (the size of labels is proportional to the weighted degree values) and Tab. 5 reports nodes degree and weighted degree values ordered by weighted degree.

The modularity algorithm based on a resolution coefficient = 3 has detected two clusters, while three clusters have been detected with coefficient = 1. These results once again demonstrate not only the complexity of the dataset, but also the potentiality of the methodology applied. If the proposed solution with a resolution = 3 seems to identify the two classes and confirm our expectations in some way, the solution of the three clusters is definitely the most interesting. The clusters 3 and 1 are those with strong characterisation, while the central cluster 2 can be considered as a transition zone between the two classes's, identifying those attributes whose classes membership is not

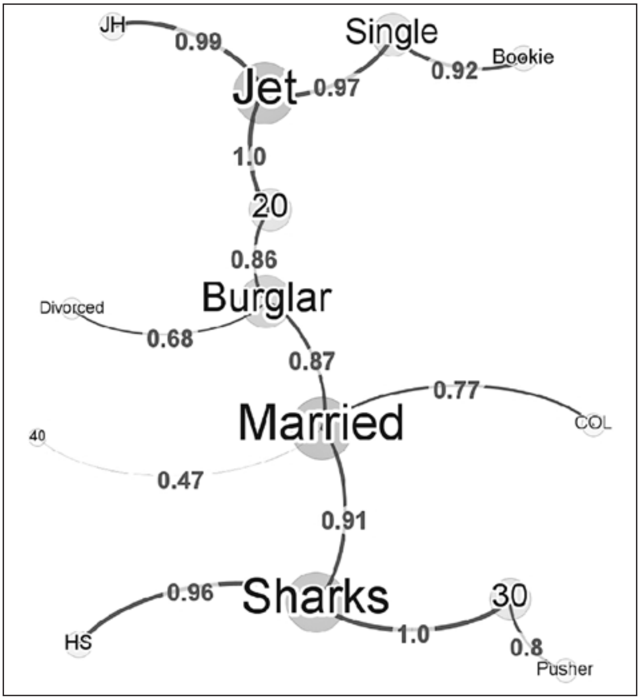

Fig. 4 – Gang variables MST (nodes weighted degree).

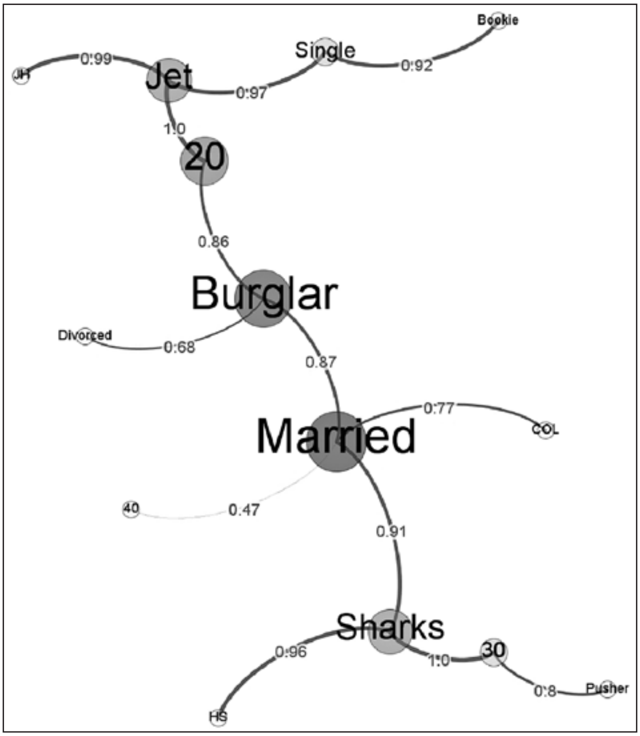

Fig. 5 – Gang variables MST (betweenness centrality).

Node	Degree	Weighted Degree
Married	4	3.02
Jet	3	2.96
Sharks	3	2.87
Burglar	3	2.41
Single	2	1.89
20	2	1.86
30	2	1.80
JH	1	0.99
HS	1	0.96
Bookie	1	0.92
Pusher	1	0.80
COL	1	0.77
Divorced	1	0.68
40	1	0.47

Tab. 5 – Nodes degree and weighted degree values ordered by weighted degree.

Node	Betweenness Centrality
Married	0.65
Burglar	0.60
20	0.46
Jet	0.41
Sharks	0.41
30	0.15
Single	0.15
40	0.00
JH	0.00
COL	0.00
HS	0.00
Divorced	0.00
Pusher	0.00
Bookie	0.00

Tab. 6 – Nodes centrality values ordered by centrality.

so obvious. The weighted degree statistics confirms not only the importance of nodes Jets and Sharks, as cluster centers, but also the importance of node Married as attribute of transition from one class to another (Tabs. 5, 6).

5.5 Records MST

Fig. 6 shows the MST of records. The labels contain, between parentheses, the membership class ID of records. Topological separation of the two classes is evident. The closely related records are very similar and may define additional groups within the main class. In Figs. 7a-b results are analysed in terms of the Modularity Statistics.

The separation of records in two classes is stably supported with values of the resolution from 8 to 4 (Fig. 7a). But even in this case it is much more interesting to analyse the results with lower resolution values which provide the finest hypothesis of possible sub-clusters. In particular, with resolution = 3 (Fig. 7b) we get three clusters: the cluster of Shark remained substantially unchanged (except for the Ike node), while the Jets cluster is divided into two sub-cluster, with the cluster in blue as a cluster of transition between the two classes and nodes Ike and Mike as those records that contain, at this level of resolution, "ambiguous" attributes. With resolution = 2 (Fig. 7c) a change of membership of three Sharks subjects, Neal, Ken and Nick occurs: now they belong to a new cluster together four subjects of the cluster detected by resolution = 3. This new cluster is separated into two sub-clusters with resolution = 1 (Fig. 7d): in this new configuration are 5 clusters. The dataset complexity is still confirmed.

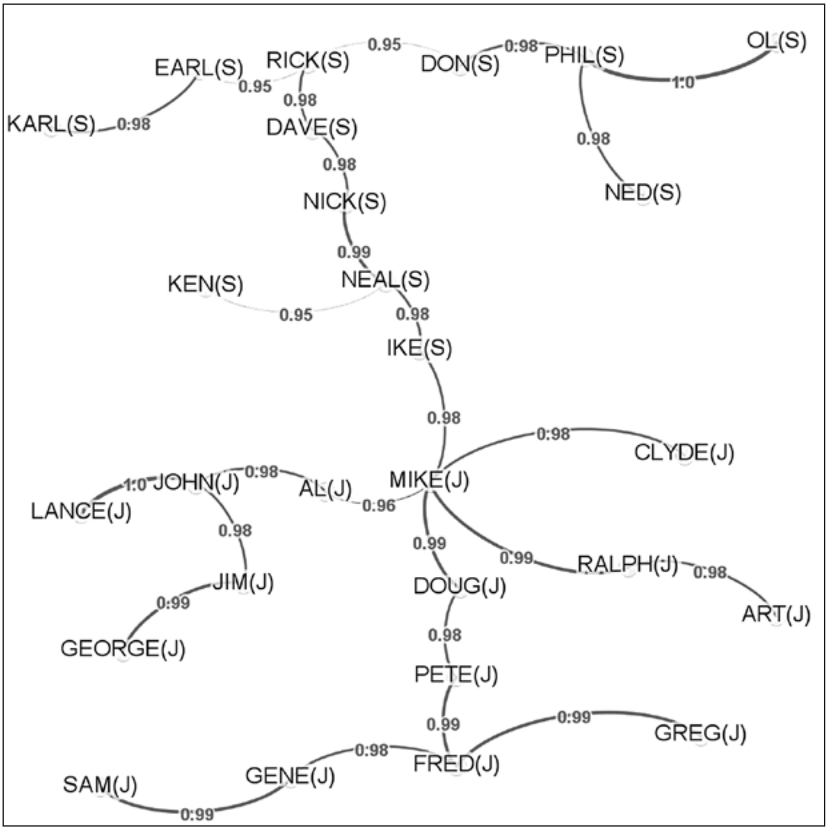

Fig. 6 – Gang records MST.

From comparison of these results we could detect two basic clusters:

1) the cluster composed of Karl, Earl, Rick, Daves, Don, Phil, Ned and Ol: we can assume that it is in the cluster that defines the differentiating characteristics of Sharks subjects;
2) the cluster composed of Doug, Pete, Sam, Gene, Fred and Greg: we can assume that it is in the cluster that defines the differentiating characteristics of Jets subjects.

Fig. 8 shows the graph of Betweenness Centrality statistics (the size of nodes and labels is proportional to the value of betweennes). Tab. 7 lists the values for each node in a descending order.

Fig. 9 shows the graph of Weighted Degree statistics (the size of nodes and of labels is proportional to the value of the degree). Tab. 8 lists the values for each node in a descending order.

Id	Betweenness Centrality
MIKE(J)	0.716923077
NEAL(S)	0.52
IKE(S)	0.507692308
NICK(S)	0.443076923
DAVE(S)	0.409230769
RICK(S)	0.393846154
DOUG(J)	0.323076923
AL(J)	0.270769231
PETE(J)	0.270769231
FRED(J)	0.218461538
JOHN(J)	0.218461538
DON(S)	0.212307692
PHIL(S)	0.150769231
GENE(J)	0.076923077
JIM(J)	0.076923077
RALPH(J)	0.076923077
EARL(S)	0.076923077
SAM(J)	0
GREG(J)	0
LANCE(J)	0
GEORGE(J)	0
KEN(S)	0
ART(J)	0
CLYDE(J)	0
NED(S)	0
KARL(S)	0
OL(S)	0

Tab. 7 – Nodes centrality values ordered by centrality.

Id	Weighted Degree
MIKE(J)	4.900000036
FRED(J)	2.960000038
JOHN(J)	2.960000038
PHIL(S)	2.960000038
NEAL(S)	2.920000017
RICK(S)	2.879999995
NICK(S)	1.970000029
DOUG(J)	1.970000029
PETE(J)	1.970000029
GENE(J)	1.970000029
JIM(J)	1.970000029
RALPH(J)	1.970000029
IKE(S)	1.960000038
DAVE(S)	1.960000038
AL(J)	1.939999998
DON(S)	1.930000007
EARL(S)	1.930000007
LANCE(J)	1
OL(S)	1
SAM(J)	0.99000001
GREG(J)	0.99000001
GEORGE(J)	0.99000001
ART(J)	0.980000019
CLYDE(J)	0.980000019
NED(S)	0.980000019
KARL(S)	0.980000019
KEN(S)	0.949999988

Tab. 8 – Nodes centrality values ordered by weighted degree.

From these analyses it is possible to conclude that the node Mike, first in both statistics, is a very significant node in the tree: Mike is central but is also the node whose the sum of links values to other nodes is the highest, and then we can assign the role of transitional element between the two classes (as the node whose distance from others is the lowest ever).

6. Conclusions

In this chapter we have proposed a data mining technique aiming to explore data in search of consistent patterns, systematic relationships and hidden associations between dataset entities (variables or records). This technique is based on unsupervised artificial neural network and provides a graph data mining methodology: a new paradigm of entities mapping aiming to create a sort of semantic connectivity map in which:

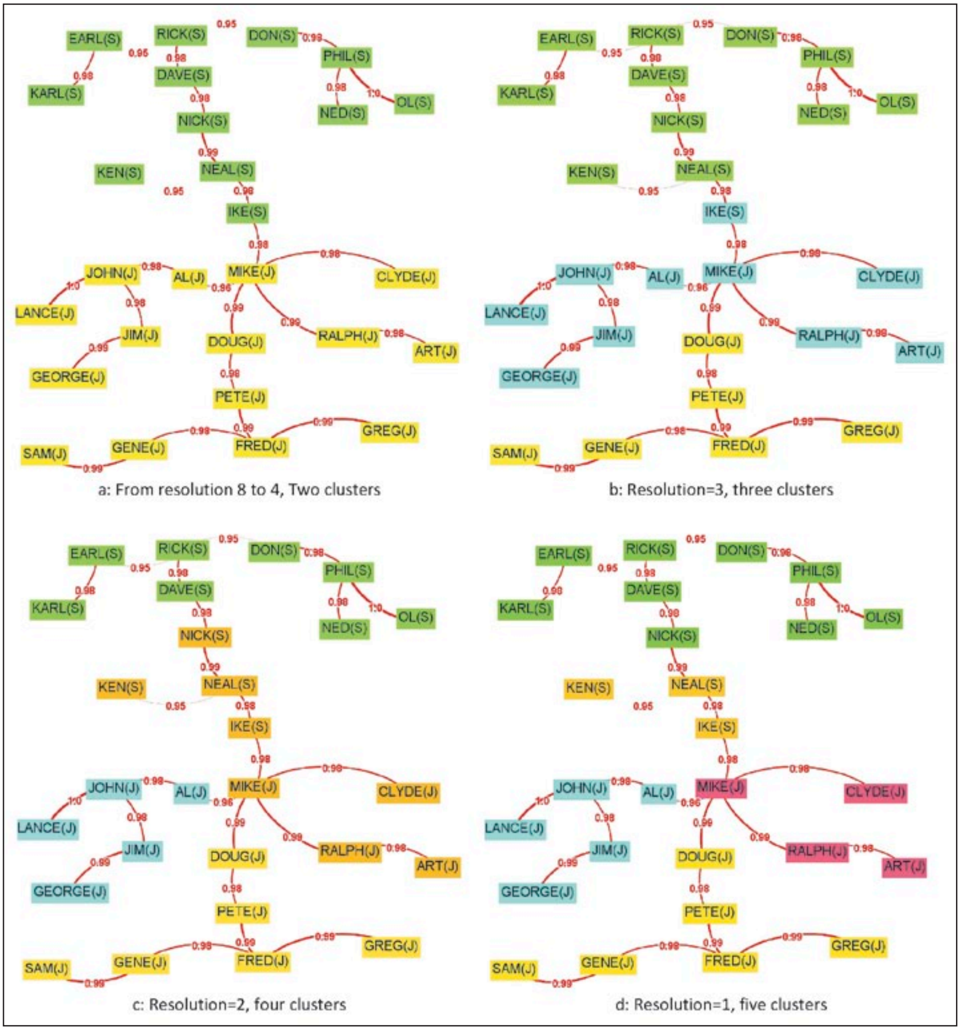

Fig. 7 – Gang records MST (modularity statistics).

1) non-linear associations are preserved;
2) there are explicit connection schemes;
3) the complex dynamics of adaptive interactions is captured.

The weights matrix of the artificial neural network Auto-CM represents the warped landscape of the whole dataset. The MST represents at this point a simple filter to apply to the weights matrix of Auto-CM system to show visually the map of the main connections of the entities of the dataset and

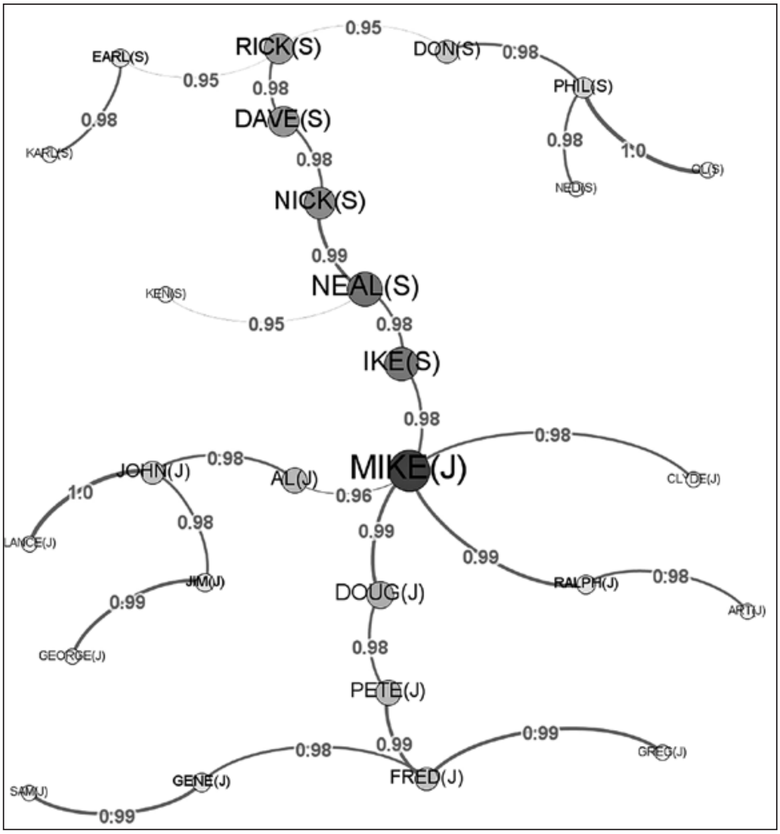

Fig. 8 – Gang records MST (betweenness Centrality statistics).

the basic semantic of their similarities. Data processing of ARCHEOSEMA project datasets, introduced in subsequent chapters of this volume, highlights the potentiality of this methodology also in research fields considerered as traditionally humanistic, for the definition of procedures of construction and validation of an interpretative model, the evaluation of its performance, its use as a valuable tool to support the exploration of alternative hypotheses and scenarios, especially in the case where hypothesis or an interpretative model cannot be directly inferred from data.

For this purpose, alongside non-supervised neural networks here used, supervised neural networks could be used in order to build models of analysis and classification. In supervised training, both the inputs and the outputs are provided. The network then processes the inputs and compares its resulting outputs against the desired outputs. Errors are then propagated back through

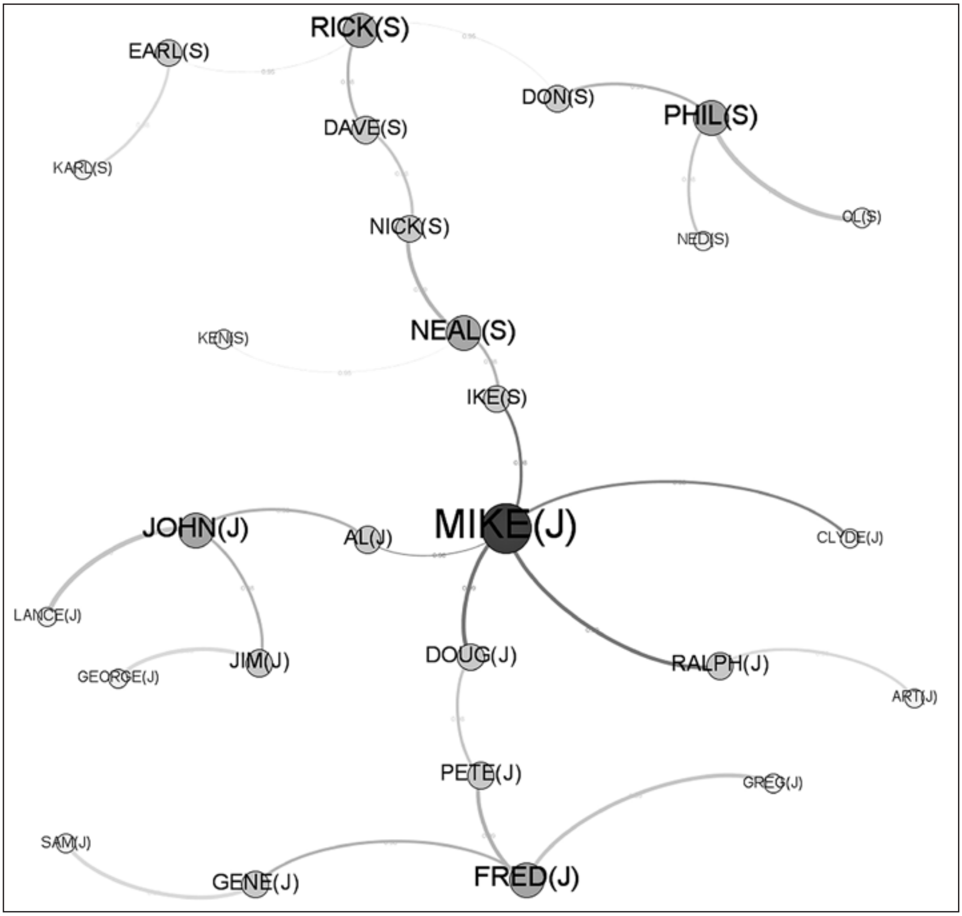

Fig. 9 – Gang records MST (weighted degree statistics).

the system, causing the system to adjust the weights which control the network. This process occurs over and over as the weights are continually tweaked. The set of data which enables the training is called the "training set". During the training of a network the same set of data is processed many times as the connection weights are ever refined. Examples of classic and important research problems that can be addressed with this networks are problems of classification/assignment 1 of n, as long as it is possible to conceptualise and define formally an input dataset, target variables, procedures of data preprocessing and a protocol of validation of the model performance.

It is important however to emphasise that the methodology proposed is not in competition with more traditional data mining techniques, it is neither an absolute alternative, nor a substitute for the expert knowledge. Researchers should use it as a tool to support their activities and assess the potentiality, even in the context of an interdisciplinary cooperation as increasingly and indispensable prerequisite within the framework of scientific activities starting from the very first stages of data collection, of formalisation of the reference database, of optimisation of stored data access procedures until the formulation of a research problem, the choice of one or more analytical models among those available, procedures for extracting a dataset to represent adequately the problem and to satisfy the requirements of the model. From a strictly epistemological point of view, the validation of the results of research methodologies proposed here will have to meet some basic criteria:

1) In case the results reproduce only what is already known in the literature, the model should be assessed in terms of implementation effectiveness and usability immediacy. If the alternative is a method that involves the application of different procedures of filtered data extraction or different statistical procedures that produce complex reports, then the model proposed here retains a significant advantage.
2) In a initial phase the proposed model cannot completely refute the guidelines of the research community, but necessarily it will contains elements of continuity. The model may suggest, to the extent established by the expert, alternative hypotheses that "explain" the phenomenon under investigation although they are based upon assumptions at the moment unfounded and/or in contradiction to what is supported by the scientific community.
3) Consequences in principle "observable" and "controllable" should be deduced from alternative hypotheses. An hypothesis should suggest some requirements or contraints, strictly experimental or not, for a "predicted" phenomenon by the model to occur or not. Controllability does not mean verifiability: the control procedures may also result in a refutation of the hypothesis as crucial procedure of importance equal to that of a verified hypothesis.
4) If we use different procedures in order to control a hypothesis, it should be necessary to evaluate the degree of convergence of the results. Although total convergence is rarely achievable, comparing the procedure can result in greater awareness of the nature and importance of each procedure parameters and the need to define the problem in a more appropriate way. There is no single and incontrovertible model that returns a unique solution to a problem. On the other hand, there is a research activity that has to deal with the development of different methodologies, to assess its ability to contribute to the development of a discipline through the reformulation of classical problems from a most promising perspective and, in the same time, through the formulation of new and unexpected research problems.

Appendix ARCHEOSEMA Lab software

All elaborations reported were performed with the research software ARCHEOSEMA Lab v 1.0, written in C ++ for Windows. The software has the following functions:

1) Calculation of connections matrices for the metrics Linear Correlation, Prior Probability e Auto Contractive Map Artificial Neural Network;

2) Definition of the Minimum Spanning Tree for each metric;

3) Minimum Spanning Tree output files in a graphml format for the visualisation and manipulation through the open source software GEPHI v. 0.8.1.

A further phase of development involves the implementation of the unsupervised neural network Self Organising Map (Kohonen 2001) and the supervised neural network Back Propagation (McClelland, Rumelhart *et al.* 1986; Werbos 1994).

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ABSTRACT

In this paper the theoretical and methodological aspects of some of the tools applied to the archaeological, geographical and linguistic problems posed by ARCHEOSEMA project will be analysed. In particular, the single steps of the process of generation of outputs, from the initial analysis of the dataset, the subsequent procedures of pre-processing and encoding of the data to the characteristics of the processing algorithms will be described. For this purpose we will use a so-called toy dataset known in the literature. Using the same dataset, we will illustrate the main output produced, Minimum Spanning Tree maps. Along with the use of classical literature measurements, such as the Pearson linear correlation and Prior Probability, both used as metrics for the generation of these outputs, we have tried to show the innovative contribution of a new artificial neural network, the Auto-Contractive Map, designed by P.M. Buscema at the Semeion Research Center.

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ADAPTIVE SYSTEMS AND GEOGRAPHIC INFORMATION SYSTEMS IN ARCHAEOLOGY: RETROSPECTIVE AND PRACTICAL APPROACHES IN SPATIAL ARCHAEOLOGY

1. Introduction

Spatial analyses could be usually performed by using pencil and paper, nevertheless nowadays it is not even thinkable to do them in that way since the use of computer helped us accomplishing these tasks in a faster way, also keeping a higher level of accuracy. Moreover, in certain cases the procedures can be so long and the amount of data so huge that it is almost impossible to perform them in a reasonable time frame. Even if the information revolution has pushed the processing capability, and the processing power is not more an issue, there are tasks that a computer is not yet able to perform and the human intervention is needed. The dream of a machine doing part of the archaeologist's job (Barceló 1993, 2009) continues on a different path and the real deal has become the existence of a "thinking machine", able to reproduce human thoughts and/or decisions.

In archaeology this could be a great opportunity not only in order to save time and to analyse huge quantities of data, but also to suggest us processes and aspects not yet discovered or formalised. The first attempts of Artificial Intelligence (AI) in archaeology followed the destiny of New Archaeology (Barceló 2009), a failure dictated by the initial enthusiasm based on something new but not yet mature. Actually, looking it from nowadays perspective, we can say that archaeology, not AI systems, was not prepared for this evolution (Lake 2010). AI systems, in fact, have now being used for several years, with thousands of successful examples in the world of research and industry. The gap between archaeological methodology and the use of adaptive systems should be filled with solid and tested methods: if a computer is able to perform a certain task it is like to say that that procedure can be formalised (Doran, Hodson 1975), but especially in social sciences this is always a very difficult and complex task (Clarke 1972). So what if a model/procedure is not yet formalised? And what if the process is not even focused? Is there a way the computer could help the archaeologist in these operations? The world of adaptive systems, along with the concept of Machine Learning, seems to offer a support for the archaeologist in different areas of interest. Since there is a huge bibliography on AI methods and techniques, we will present here only few examples and their applications in the archaeological field, dividing their use into three main groups: 1) classification/data mining; 2) shape recognition; 3) spatial analysis.

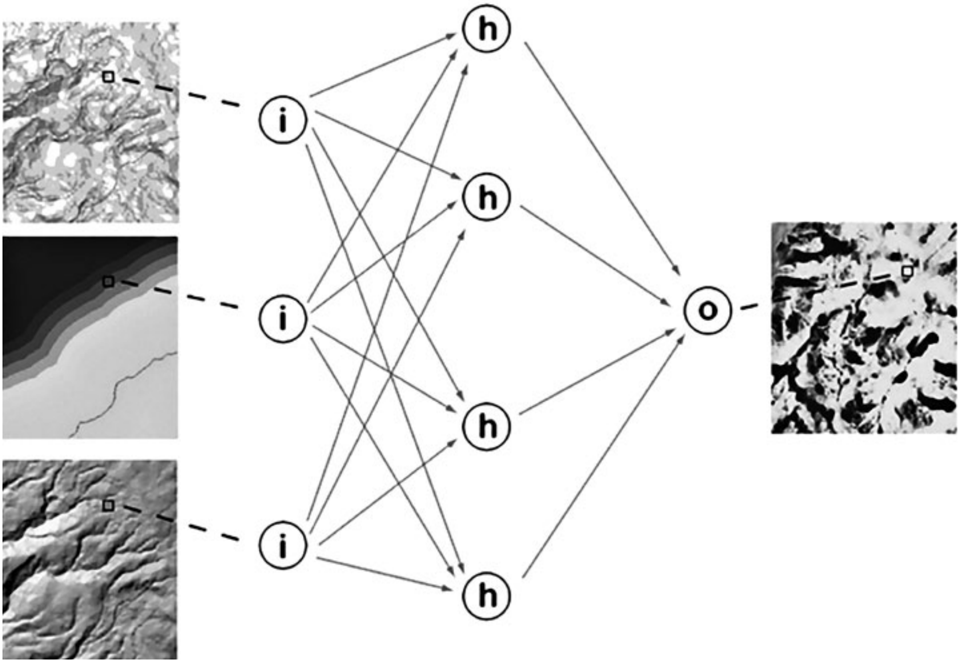

Fig. 1 – Example of ANN with three input raster layers and one output map.

1.1 *From data to knowledge*

Data mining and classification with the use of AI are maybe the paths more often chosen by archaeologists. The inner nature of the archaeological record is to be always fragmented and the "whole" dataset must be conceived as a part of the original data. For this reason, finding relationships between records, from artefacts to sites distribution, is one of the archaeological main aims. Unfortunately these aspects are not always recognisable at a first look and there is the necessity to discover "hidden" relations into datasets, trying to find a model suitable to match records. It derives that datasets availability is a necessity for these kinds of exploration, but with the Internet era the amount of data has become easily reachable in a worldwide scale and operations of data mining allow researchers to gain data also for testing models (Wurzer *et al.* 2013).

By using sources like ethnoarchaeology, that studies living societies to help explain cultural patterns in the archaeological record, it is also possible to increment these datasets adding examples to create a database of real experiences of hunter-gatherer populations, useful for the study of certain time periods (Binford 2001). The need to classify this enormous amount of

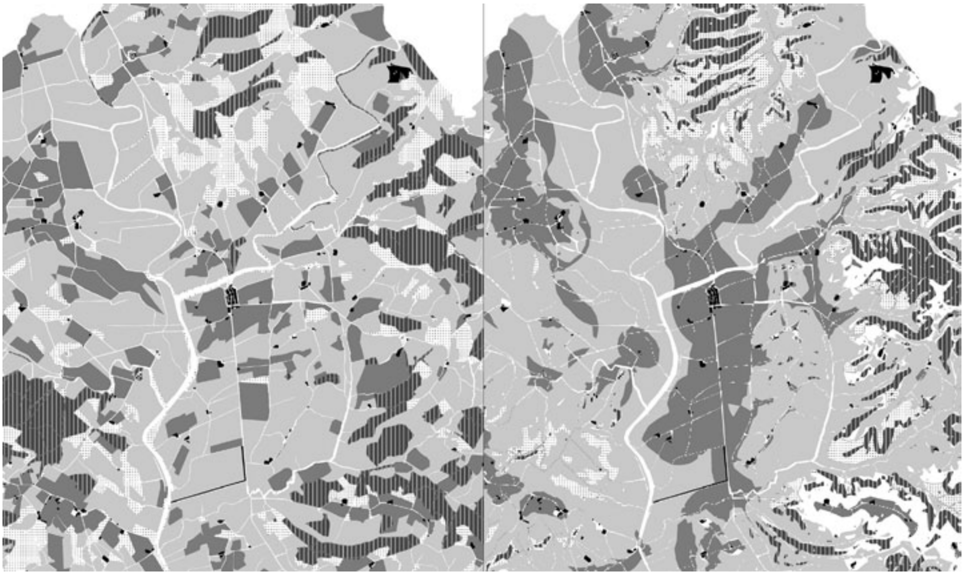

Fig. 2 – Comparison between the actual land use of Buonconvento area in XIX century (left) and the predicted one (right).

data, however, encounters the problem of how to do it in a critical way: even apparently simple tasks, like classifying and identifying pottery fragments, at a certain point become too complex and even if every new record adds more information, it also adds more complexity.

At the beginning of the 1980s some researchers tried to find solutions to these problems with the use of expert systems, based on different algorithms and applied on different case studies, like pottery (Bishop, Thomas 1984; Vitali, Lagrange 1988), other kind of artefacts (Ganascia *et al.* 1986; Grace 1989) or animal remains (Brough, Parfitt 1984; Baker 1987). The approaches varied a lot: from being based on artefacts shape similarity to chemical composition of the fabric, for example, obviously including also the time variable and all the problems related to ageing remains.

Beside expert systems or the so called "intelligent databases", with a limited applicability for computational problem solving, different methods based on Artificial Neural Networks or ANNs started to be applied in different archaeological contexts at the beginning of the 1990s (Gibson 1992, 1996) even if at the end of the decade they were not yet extensively explored (Van den Dries 1998). The use of these techniques, which in the last decade have been used more extensively in archaeology, especially due to their ability to use partial and incomplete datasets, can be divided in two groups based on their type of "learning" and their consequent different destination of use: supervised or unsupervised.

The methodologies related to the first group, in particular the Self-Organizing Maps or SOMs (Kohonen 1984), due to their characteristics, have been mostly used for clustering, classification and taxonomy. For simplicity we can say that these methods are mostly based on the concept of similarity, on different parameters, that lay in between the records of a certain dataset. On the other hand, supervised systems focus their strength on the process of "learning" by examples. In this group we can include techniques like Feed Forward/Back Propagation, Bayesian, Perceptron and many other types of networks. It is clear that, in this case, the necessity of a consistent sample to train the network is fundamental: the more the records are, the more the result will be accurate.

Some typical examples of ANNs in archaeology, mostly based on unsupervised training methods, can be found in the study of different kinds of ceramics (Lopez-Molinero *et al.* 2000; Fermo *et al.* 2004), in which, coupled with the use of Gas chromatography/Mass spectrometry or similar archaeometric techniques able to recognise the elements present in the fabric, the association is made by the similarity of the materials that compose the pottery (clay, glaze) in order to identify, for example, the place of provenience. One last aspect that should be at least mentioned is the Fuzzy Logic theory implementation (Zadeh 1965), another important part of the AI that has been involved in several archaeological case studies on classification, allowing to overtake the "classical" true/false, 1/0 approach (Barceló 1996) by allowing an element to be "partially" part of a certain group.

1.2 *Toward a territorial approach*

The applications presented in the above paragraph do not take in account the location or the territorial aspects of the records, and also in the case of archaeological sites studies they were considered only as entities characterised by certain variables, but not by their position in the space. Spatial analyses can cover a huge quantity of aspects of the investigation, going from intra-site analyses, i.e. the location of an artefact in the site, to the organisation of the site itself, its relationships to the surrounding sites and so on. Moreover, we have to consider that not only the coordinates are fundamental, but also the chronological aspects that are deeply related with the location. We must remember that the archaeologist, for example studying archaeological sites location patterns in a certain area, can investigate them in a synchronic way, analysing sites of the same period, but also in a diachronic way, by looking for relationships between sites of different periods, adding a time variable. In this case, the use of GIS is an aspect that characterises, for their inner nature, almost all of the applications presented in this section.

One of the major applications of adaptive systems in this field is the one related to shape and pattern recognition (Bishop 1995), usually in combination with remote sensing, satellite images and aerial photogrammetry, in order to find ancient evidences on the earth surface that can help us in the reconstruction of the past. The analysed evidences are mostly artificial (De Guio 1996; Davino *et al.* 1999; Alexakis, Sarris 2010; Cavalli *et al.* 2012), like buildings, roads and human settlements/sites in general, but also natural, like paleochannels, ancient land assessments and so on; of course in this case the type of evidence is related also to the level of detail of the used data. One of the most fascinating fields, however, is maybe the one of predictive modelling and simulations in a spatial context. Trying to individuate and/or to recreate the processes that led to a certain settlement pattern means, in a certain way, to understand some aspects of how humans thought in the past, which were their priorities and how they conceived life. A real territorial approach in archaeology, with the use of AI in combination with GIS, is quite recent and not yet explored extensively, while adaptive systems were often used as a support to territorial analyses (Ramazzotti 1999, 2013).

Some examples that take in account the space aspect, even if not in a GIS environment but mostly in a pseudo-real space characterised by some variables like presence of resources and provisions or communication channels, are based on simulations. Several examples in this field were attempted (Doran 1990) with different methodologies, like multi-agents systems, that can simulate actions/reactions in relationship with the variables that characterize, for example, the environment. This characteristic has been used, even if some see a limited potential for agent-based modelling in archaeology for the tendency to make human societies too static, especially in prehistoric field for the study of sociological and cultural changes in a multi-actor environment (Zubrow 2003, 173-180) or for replicating hunter-gatherer decision-making strategies, resource-sharing strategies, and the impact on population dynamics (Costopoulos, Lake 2010).

At one point researchers started to consider the possibility to couple adaptive systems to the use of GIS (Reeler 1999). The field that maybe has been more affected by this tendency is the one of predictive modelling that in the last years has grown extensively in archaeology, making an intense use of the adaptive systems, in particular ANNs (Ducke 2003; Van Leusen *et al.* 2005). Even if these approaches are mainly focused on predictive purposes, we think that they can also be used for the study of ancient settlements, involving spatial analyses in a more extended form. The training process in fact, even considering all the problems related to the "black box", could be a way to compare, and so understand, settlements patterns.

2. ANNs for the study of ancient settlements patterns

While the previous papers on this research were mostly based on the methodological side, here the focus will be more on results analysis. A first version of the presented methodology can be found in Deravignone, Macchi (2006), after which several technical aspects were improved and the case studies and fields of applications extended. A very brief explanation of the methodology is reported here in order to better understand the rest of the present contribute. The main idea was to train a feed forward ANN in order to "understand" the dynamics that lead to a certain settlement pattern by training the network with some variables that characterise the single features (archaeological sites) of the pattern itself, like geo-morphological aspects, proximity to other kinds of settlements or resources and so on.

The first attempts were made with medieval hilltop settlements (castles), of southern Tuscany (Italy), thanks to the huge database available made by the University of Siena since the beginning of the 1990s. The training pattern was constituted by real castles (identified by the value 1), and a set of null or "negative" points (identified by 0): in this way the net learns all the characteristics of the "real" sites and it is able to recognise the areas more suitable for them (Fig. 1).

All the values are originated from raster datasets, counting not only the site itself but also the surrounding areas, using different distance radiuses, for more than 60 total input variables. Raster files were also used during the final phase where they are processed with the trained network, and an output probability map, with values from 0 to 1, is produced.

2.1 *Methodology improvements and new case studies*

On the technical aspect one of the major improvements to the previously explained methodology was the creation of the SNNSraster Manager software (freely downloadable from http://sourceforge.net/projects/snnsraster/) that allows everyone to easily perform the final part of the process. Once again the Open Source approach was followed and the multi-platform aim was respected since the whole procedure is achievable under Windows and Linux operating systems. The total replicability of the analysis process has been preserved, making the procedure even easier than before and with no particular needs regarding the GIS software, since the standard and open ASCII file format is still used. In this way the whole process has became faster, reducing also the number of steps in order to simplify the method, from data creation to analysis results.

On the data side, the list of variables has been increased with new values, including Landsat satellite images, and an important decision was to couple the laboratory testing, made with castles excluded during the learning procedure and used as a test set, with field surveys. In order to accomplish this, the analysis area was extended to the total area of the ancient Volterra diocese, focusing on areas with a scarce presence of sites on the archaeological map. The reason is mostly imputable to the extreme difficulty of surveying those areas with a standard method, especially due to the strong forestation that characterises them. Surface surveys in high probability areas lead us to the discovery of several new sites of the same period used for training (1150-1300 AD), basing especially on built up evidences and on the numerous pottery findings. After all these tries, there was inevitably the need to test the method on a completely different context, in order to see if our results were so significant to spread the method also to other case studies. The opportunity was offered from a study on northern Norway pit dwellings in collaboration with Prof. Blankholm, University of Tromso.

The choice was perfect thanks to the different context, different type of site (only present on the seaside) and historical period (Neolithic and Early Metal Age). That was also a good occasion to formalise the procedure named "Grosseto predictive method" (Deravignone *et al.* 2014). The first step was to perform new ANN analyses with a small sample of already known sites, covering the total area of Senja Island, Troms County, in northern Norway. After that, two survey sessions were performed in 2010 and 2012, focusing on high probability areas along the coastline. Due to the different type of sites, different variables were used.

2.2 *ANNs and historical sources for land use studies*

A different attempt has been done applying the same methodology to land use (Deravignone 2011a, 2011b) where, instead of point pattern analysis, the input was constituted by the single cells of land use; moreover, while the previous approach was based on only one output (castle/not castle), in this case an output for every single land use was necessary. In order to accomplish this, the land use was simplified to five main categories: built up, agriculture areas, specialised cultivations, pastures and woods. The built up was used only in training process while the rest were used both in training and back-casting phase. Also in this case, in fact, an important aspect was the distance from inhabited areas, towns, villages or even single farms. The idea was to train the net on a certain area and to apply the trained network on another similar context. For testing the results the use of "Leopoldino" cadastre, from the first decades of 1800, was fundamental. In this cadastre the land use of the various parcels is reported in detail allowing to see if and how the results were, with the real XIX century land use. After converting all the parcels in raster format, a net was trained with data from S. Quirico d'Orcia area, while the test was done on Buonconvento area, both located in Siena province in southern Tuscany (Fig. 2)

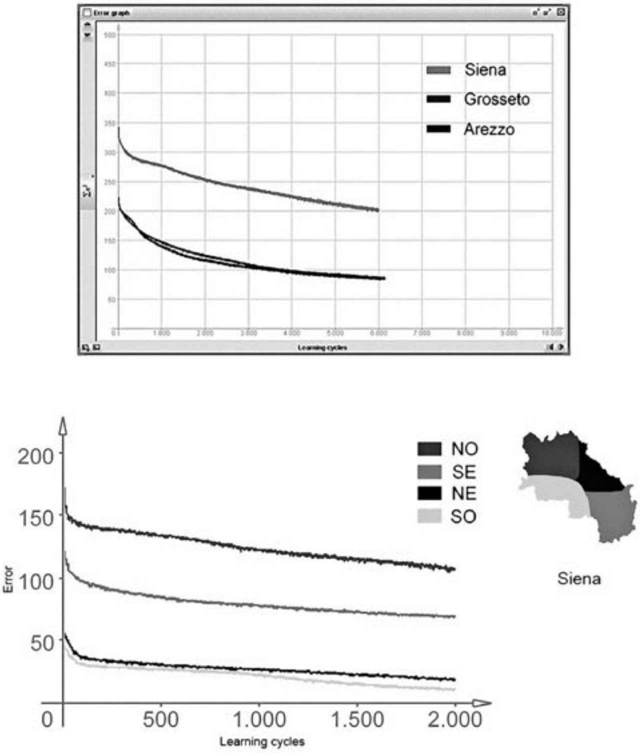

Fig. 3 – Error graphs relative to the ANN training in the Provinces of Siena, Grosseto and Arezzo, and the focus on the Province of Siena, divided in four sub-areas.

The results were extremely interesting and gave us the idea of a society where distances were more important than today, and the closeness of the house or community to the field was very important. Here we can immediately recognise a classical model of land organisation, where the best suitable land is cultivated, due to the type of soil or good slope and exposure, while the rest is left uncultivated as woods or pasturelands. We can easily see an example of Von Thunen model where also the role of distance is easily visible: starting from the city, where the closest areas are dedicated to specialised cultivations, we reach the more distant ones, where the situation tends to have more "natural" aspects that do not need human intervention. The use of historical sources was very useful in this first experiment in order to test the results using them as a litmus paper. Once that the methodology has been tested, in fact, the method can be applied to similar contexts where we do not have historical evidences, hopefully with the help of other methods like palynology or other archaeometric methodologies.

3. Conclusions and empirical evidences

The use of feed forward ANNs for the study of ancient landscapes and settlements patterns has been giving very interesting results; both the survey sessions results, for hilltop settlements in Italy and pit dwellings in Norway, were very encouraging, and after few years of testing we are now able to do some more in depth considerations. Besides the predictive approach we can also state something about the utility of these kinds of spatial analyses for the study of ancient settlements: while the diachronic analyses did not give significant results, the application of a trained net on a different context gave us some food for thought. An interesting aspect, for example, comes out looking at the differences between the training of the whole area, constituted by Grosseto, Siena and Arezzo provinces, and the training of the singles provinces. Analysing the error graph it is possible to notice a higher level of error related to the Siena area training, compared to the other two. For this reason it was decided to investigate more in depth the reason, dividing the area in four, partially overlapped, parts and analysing them singularly (Fig. 3).

The visible differences in the error graphs can be explained by a more complex situation that, even if determined also from variables not used in the training phase, is a sign of the complex social dynamics derived from the presence of an important city like Siena, also taking into account the proximity of Florence on that side. There are also many other interesting aspects that should be explored, like the presence of many high probability areas containing a high number of aerial photography anomalies not yet checked or surveyed, or the presence of numerous farms, mostly from the XIX century. The exploration of this field is far to be concluded, but the exigency of testing more case studies and analysing results, with the help of different analyses in order to look for social dynamics and along with the help of strong historical sources where available, is expected.

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ABSTRACT

For several years now archaeology has made use of methodologies based on Artificial Intelligence (AI) and Artificial Adaptive Systems (AAS). However, there are still only a few experiments that involve the spatial aspect, and in particular spatial analyses of the territory. Moreover, we are often faced with theoretical approaches, procedures that cannot be used or repeated by the scientific community because they are based on proprietary or undivulged algorithms. The first part of the paper is focused on a short historical retrospective of the applicative experiences of AI and GIS, from the "new archaeology" pioneers to the latest experiments in predictive approaches. Subsequently, we present an "open source" application, both from the software as well as the procedural point of view, oriented to the creation of predictive maps and focused in particular on the study of ancient settlements.

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A COMPUTERISED ATTRIBUTION METHOD

1. Stylometry and computerised attribution methods

This research originates from the consideration, initiated less than a decade ago, of the possible interaction between Philology and Information Theory (Canettieri *et al.* 2005, 2006, 2008; Canettieri 2012). Its purpose is to propose systematically a Unified Theory of the Text (UTT), whose application consists of the possibility of measuring the distance existing between two or more texts on different levels: graphic, phonetic, morphologic, and semantic. On a theoretic level, for each one of these scales the range of distance fluctuates from 0 to 1, where 0 indicates that two texts are identical and 1 that they are completely different from each other.

Based on the he UTT it is thus possible to evaluate, with a single automated operation:

1) the distance existing between manuscripts or copies of a same work (taking both the errors and the variables into consideration and providing them with differentiated weights);
2) the distance existing between texts of a same author, extrapolated from the same or from different works (authorship intertextuality or intratextuality);
3) the distance existing between texts belonging to the same genre, school or poetic movement;
4) the distance existing between different works that cannot be associated with each other in an intertextual manner but present a certain degree of intertextual relationship.

The values that can be obtained are various and articulated, but each homogeneous group of results can be visually represented by means of a graphic tree structure where the textual objects that present a certain similarity with each other are gathered in clusters and where the similarities gradually decrease while proceeding from the tree leaves up to its roots.

An example of representation is offered by the Italian Duecento Poetry tree, which has been variously reproduced on various occasions in the works indicated above and for which it is possible to visualise the integral version online. Moreover, it is not a coincidence that, within the UTT frame, the computerised procedures based on the basics of Information Theory -which have been adapted by Roman Jakobson for the linguistic and literary subject, heuristically appear to be the most efficient (Jakobson 1960; Van de Walle 2008). Such procedures provide, in effect, by definition discriminating elements in the gathering of texts based of their distance.

The UTT finds practical confirmation and application in the field of authorial attribution, where the interaction between scientists in text, mind, physics and mathematics may offer important contributions to the community. I take the liberty to refer to the work that I consider the most relevant of my "philological" works, the debate held during the trial for the homicide of Massimo D'Antona, which can now be listened on Radio Radicale's website and to which I took part as an expert witness for the defence: in such case, the study of the attribution problems allowed the full acquittal before of the Court, after nine month of imprisonment, of one on the accused subjects, who had been implicated in this trial by an attributive appraisal based on an erroneous methodology. In fact, dealing with anonymous documents or with works of uncertain attribution represents a great, important and useful challenge for philologists. The attribution process has been described as «the operation, which culminates in a critical judgement and which aims at, in the absence of or to completion of or to check the historical records, the identification of the author of an artefact, that is the assignment of the authorship of an anonymous work to a specific producer or the identification of the historic-cultural environment in which this artifact was conceived and produced» (Besomi, Caruso 1992).

Such procedure entails the confrontation with a series of problems, as for example:

1) a text is attributed to different authors by different witnesses (contrasting attributions);
2) a text has been transmitted in an anonymous form and it is necessary to ascertain its author;
3) a text has been attributed to an author, but there are strong doubts that it might have been written by someone else and it is thus necessary to ascertain whether it is authentic or apocryphal;
4) a text attributed to an author might contain interpolations of one or more different authors and it is thus necessary to understand which sections of the text were interpolated and to whom they ought to be attributed.

In an attempt to resolve such problems, philologists have resorted to traditional tools of textual analysis, first of all, in regard to antique texts, the *stemma codicum*, used to identify the most reliable witnesses or the point in the tradition where the attributive disturbance occurred: it is clear that the correct attribution, in terms of stemmatics, is related to the selection of variables and cannot be founded on the amount of the conveyed manuscripts but rather on their critical quality. Furthermore, when the *stemma codicum* consists of two branches, the choice would generally go to the less famous author, since the condition of minor notoriety has the same value as the concept of *lectio difficilior* in textual reconstruction. The aetiology of the attributive error has also been analytically described in some *ad hoc* essays (Pulsoni 2001).

In addition to the stemma, in the field of traditional attributive science, other criteria are used, which are usually classified in "external" and "internal" criteria (Erdman, Fogel 1966; Contini 1984): «Attribution studies distinguish conventionally between internal and external evidence. Broadly, internal evidence is that from the work itself and external evidence that from social world within which the work is created, promulgated and read; […] External evidence […] covers the following kinds: (1) Contemporary attributions contained in incipits, explicits, titles, and from documents purporting to impart information about the circumstances of composition […]; (2) Biographical evidence, which would include information about a putative author's allegiances, whereabouts, dates, personal ties, and politic and religious affiliations; (3) The history of earlier attributions of the work and the circumstances under which they were made. Internal evidence […] covers (1) Stylistic evidence; (2) Self-reference and self-presentation within the work; (3) Evidence from the themes, ideas, beliefs and conceptions of genre manifested in the work» (Love 2002, 51).

The first ones, which are by nature substantially related to the content, assist in evaluating whether the information contained in the text correspond to historical data: they include evidences from other authors, historic-cultural or biographical references within the text, and analysis of the sources. The internal evidences, on the other hand, include formal aspects such as rhetorical, metric, stylistic and intertextual analysis. Well-known is the method for the attribution of artistic works implemented by Giovanni Morelli and based on the internal criteria of stylistic particulars (ears, hands, folds of the clothes, etc.), that, according to Morelli, would have brought to the individualisation of the style of a specific artist, distinguishing him from his imitators (Ginzburg 1979, 57-106).

Among the internal criteria is also included the stylometry, i.e. the quantitative and statistical study of the literary style, in the present research intended as «all the formal features characterising (in sum or in a particular moment) the expressive manner of an individual or the writing manner of an author», therefore meaning the expressive and creative features that are typical of each individual rather than «all the formal features characterising a group of works, constituted on a typological or historical basis» (Segre 1985). Stylometry is based on two premises: in the first place, it should be possible to quantify, and thus to measure, the stylistic features of a text; in the second place, the texts of the same author should present similar features with each other. For example, if the suspect exists that an author did actually not write a text that is traditionally attributed to him, both such text and the other texts written by the same author could be analysed and compared through different attribution methods. In the event that an important statistical difference between the text under study and other texts certainly written by this author exists, this could represent the evidence that the uncertain document has not been written by the hand that wrote the other documents.

Stylometry is a procedure of analysis that, at this point, is extensively applied to literature: since it aims at identifying, measuring and confronting the features of what we call style, it proposes to decompose the text in order to understand which stylistic features distinguish a work and its author from other works and other authors. In the stylometric procedure the data interpretation follows an analytic stage that includes, along with the usual tools, also the statistical representation and the comparison of the numerically elaborated results. The numerical comparability allows a direct and precise confrontation of texts, authors and passages of a same work or pertaining to the same author. The proposals that followed each other over time suggested the analysis of different graphic/linguistic elements, ranging from the average sentence length, expressed in number of words, characters, or syllables, to the study of the vocabulary, by counting the average length of words, expressed in characters, the average number of syllables per word, the frequency of monosyllabic words, the frequency of empty words (that thus do not depend on the content, as in English the words *a, all, an, and, any, as, but, by, in, it, no, not, of, that, the, to, up, upon, with, without*).

Some other stylistic features were considered to be significant, such as the percentage of each different part of the discourse (nouns, verbs, adjectives, etc.). Recently, the measurement method of the "intertextual distance", introduced by Labbé and Labbé, has raised a passionate debate in France. After realising a complete lemmatisation of the texts under study, the two scholars have analysed the distance occurring between the obtained dictionaries: the shorter the distance, the greater the possibility that the two texts are attributable to the same author, or belong to the same literary genre or to the same period, or relate to the same subject (Labbé, Labbé 2001). Some statistical models have been developed to evaluate the "lexical richness" of an author, the average distance in which new words are generated in a text, the frequency of *hapax legomena* and *dislegomena*, the so-called "Weighted Precision/Recall" (WPR) lexical units reports, such as, for example, the relationship between the Rate of Occurrence of an English article at the beginning of a sentence and the number of sentences, the relationship between the Rate of Occurrence of a conjunction followed by an adjective and the overall occurrences of the same conjunction, or the preference given to a synonym rather than to another (for example the relationship between the number of occurrences of *any* and *all* and the occurrences of *any*), etc. (Mendenhall 1887; Yule 1938; Williams 1940; Fucks 1952; Wake 1957; Ellegård 1962; Brinegar 1963; Mosteller, Wallace; Fuks, Lauter 1965; Morton 1965; Somers 1966; Antosch 1969; Brainerd 1973; 1974; Bruno 1974; Sichel 1974; Morton 1978; Kjetsaa 1979; Marriot 1979; Larsen *et al.* 1980; Burrows 1987; Hilton 1988, 1990).

The comparative application of the different methods to texts of *Known authors* has pointed out that the phrastic analysis does often produce unreliable results, also because of the practical definition of the concept of "sentence" as a unit bounded by two gradually different elements of punctuation, like two full stops, dot and exclamation (or question) mark, dot and semicolon, two commas, etc. (Ellegård 1962; Mosteller, Wallace 1964; Marriot 1979). The lexical richness turned out as well to be insufficiently probative, since many of the experiments conducted on texts of the same known author have highlighted the possible reliance of this element on the practiced genre: it is different to write a letter, a newspaper article, a poem or a novel. Nevertheless, the interference between the author's typical stylistic features and the features related to the content or to the genre of the text (either literary or not) represents a very sensitive issue (Clement, Sharp 2003).

On the other hand, how the stylistic elements are stable over time and how they are influenced by each individual's spiritual evolution, as well as the way in which they consciously or unconsciously change over time still need to be investigated. Certain is that, in order to apply efficiently this type of analysis, the compared texts need to be, as well as comparable in terms of genre, language and content, long enough, and the analysed stylistic features need to be structural, frequent, easily measurable and sufficiently independent from the author's conscious control (Bailey 1979).

In this sense the WPR, the frequency of empty words, the computation of elements outside of the conscious control, both the frequency of the use of certain letters rather than others, and the investigations conducted on the relative frequency of morphemes and minimal linguistic segments have shown good differentiation and assimilative skills. We know that it is now possible to automate analysis procedures aiming at the authorship attribution through an increasingly efficient technology that has multiplied exponentially the calculation rapidity, providing opportunities that were still unthinkable few years ago; so, even though many of the currently employed strategies remain essentially measurements of the words (in terms of length, rate of occurrence, frequency ratio) and of the sentences (number of words and average length in terms of characters), stylometry has led to the awareness that a certain number of textual structures can be described in quantitative terms and, consequently, various tools of mathematics and statistics have been introduced in attribution science: so, gradually, the interest has shifted from indicators based on discrete linguistic components to methods in which the text is analysed through models rather not dissimilar to those in use to compare other chains of symbols, as for example the DNA.

In this view, the systems applied since the beginning of the XXI century have been using series of units, also linguistically non discrete ones, analysed through methods that range from Markov's chains to the compression algorithms, the Bayesian classifiers and, finally, to the numerous methods of "Machine Learning", a field of Artificial Intelligence that realises algorithms based on the learning of data coming from different types of samples and on the following statistical evaluation of the relationships between the observed variables, in order to achieve the data summary and then new knowledge. In all these approaches the text is considered as a sequence of symbols and the lexical elements have no more meaning than other symbols' aggregates, while the statistics of the sequences of *n* consecutive characters (the so-called n-grams) naturally appear as fundamental subjects of the research (Khmelev, Tweedie 2001; Benedetto *et al.* 2002; Keselj *et al.* 2005; Basile *et al.* 2008).

In a competition organised in 2003 by Patrick Juola, different attribution methods were compared by applying them to the same composite *corpus* of texts "Ad Hoc Authorship Attribution Competition" (AAAC): the best results were obtained by scholars who had applied to the traditional stylometric parameters (unstable words, empty words, most frequent words) a machine learning method called Support Vector Machine. Juola himself provided a valuable guide for the questions of authorship attribution, which can also be seen as the theory underlying the JGAAP (Java Graphical Authorship Program), a downloadable program for analysis, text categorisation and attribution, written in the Java programming language (Juola, Baayen 2003; Juola 2006).

JGAAP uses a modular architecture, whose base levels are the graphical standardisation/regularisation of the text Canonicalisation, the stylometric element that is meant to be processed (Event Set Generation), the modality of selection of the element (Event Culling) and the statistical analysis of the acquired data (Analysis). Each one of these levels is handled by one single generic Java class: the Canonicalisation module is so handled by the canonicaliser class, the Event Set Generation by the Event Drivers class, the Event Culling by the Event Cullers class and the Analysis module by the Analysis Methods class. Among the Event Drivers we may select single characters or contiguous n characters gathered from a sliding window (Characters and Character Grams), as well as single words or contiguous n words (Words and Word Grams), the first word of each sentence (First Word in Sentence), the words with a variable number of letters or vowels (M-N Letter Words and Vowel M-N Letter Words, where *M* and *N* are variable parameters), the empty words or the function-words used in Mosteller and Wallace study on the Federalist Papers (MW Function Words), the rare words, such as those employed once or twice in each document (Rare Words), the sentence length measured in words (Sentence Length), the suffixes, understood as the last three letters of each words (Suffixes), the syllables per word, with a very simplified system where each vowel is counted as a syllable (Syllables per Word), etc.

In order to select the analysis modality it is necessary to activate the function Event Culling, which allows to sound out, in all the documents, the least common n phenomena or the most common n phenomena or even the phenomena present in all the samples (Least Common Events, Most Common Events, Xtreme Culler), etc. It is then possible to select, among the countless types of statistical analysis, among which we bear in mind Burrow's Delta, Support Vector Machine (SVM), in its Gaussian version (Gaussian SVM) and in its linear version (Linear SVM), Linear Discriminant Analysis (LDA), Markov Chain Analysis, Naïve Bayes Classifier, PCA, SPCA, WEKA. Some methods require the selection of the Distance Functions such as the Cross Entropy, the Lempel-Ziv-Welch Nearest Neighbor Classifier and many others.

2. Application to Romanic texts

Although the good performance of many computer methods of attributive analysis has now been demonstrated and although such methods are employed extensively and with good results in other areas of literary studies, especially in Anglo-Saxon ones, their application to the texts of the Romanic literatures (whether medieval or not) has not received sufficient impulse yet. In several works in collaboration with physicist Vittorio Loreto of La Sapienza University of Rome, we have been using methods based on the Information Theory, applying to the texts of Italian poetry a zipping program and different programs for the elaboration of phylogenetic trees (Canettieri *et al.* 2005; 2006; Canettieri 2011; 2012).

The results have been overall very satisfying, with percentages over 90% for the known author on known author attribution. As has been demonstrated, in this type of approach the outcome of the process is constituted by a tree in which the analysed elements are grouped on a scale in clusters, from the closest to the farthest. Reckoning the advancement of researches in the already boundless field of authorship attribution, I have been able to verify in first person the possibility of extending and integrating such researches. So, I have been using the program developed by Juola to test the different "known author on known author" methods, also in order to achieve results more solid than those obtained previously.

I have thus developed a series of experiments in which I have tried to verify how a specific approach was able to identify the author of a text string, taking into account the crucial variables of this type of research: text length, number of examples, genre variety. I have also recently extended the research, in collaboration with two scholars of authorship philology, to twentieth-century authors, in order to validate or falsify the method in the event of ascertainable authorship diachrony. Although I have not crossed all the possibilities offered by the system yet, I believe that, for early Romanic texts, considered the huge graphic oscillation, which makes each exclusively lexicon-based analysis much less accurate, the most productive approach is the one that computes pairs of letters (Characters Bigrams), using Linear SVM as a method of statistical analysis and selecting the items with Xtreme Culler: the application of these parameters to different *corpora* has in fact always produced excellent results, which I will now briefly describe.

The first, extremely simple experiment only concerned the *Roman de la Rose*. The text was divided into parts of about 1000 lines each, up to v. 13058. The first documents, named *Roselorris (1-4)*, contained the part of the *Roman de la Rose* attributed to Guillaume de Lorris; the remaining nine documents, named *RoseMeung (1-9)*, the part attributed to Jean de Meung. Then two files were constituted in the *Known Authors*' box: all the *Roselorris* documents were included in the first file, named *Guillaume*, all the *RoseMeung* documents in the second one, named *Jean*. The experiment consisted in rotating in turns all the documents, eliminating them one by one from the *Known Authors*' file and entering the corresponding removed document in the file of *Unknown authors*. In the first test, for example, *Roselorris1* was listed among *Unknown Authors* and *Roselorris2*, *Roselorris3* and *Roselorris4* in the *Known Authors*' file; in the second test, the same procedure was followed by placing *Roselorris2* among the *Unknown Authors* and *Roselorris1*, *Roselorris3* and *Roselorris4* among the *Known Authors*, and so on, by rotating the texts to be verified. The results gave 100% of correct attributions: all the documents named *Roselorris* were attributed to *Guillaume* and all the documents named *RoseMeung* were attributed to *Jean*. In addition to the functionality of this method for issues such as the one here proposed, this simple experiment demonstrates, if it is still necessary, that the double authorship of the *Roman de la Rose* cannot be called into question.

The second experiment involved troubadours' lyric poetry, with much smaller portions of text. Each one of the first ten documents, named *Guglielmo (1-10)*, contained a *vers* of Guglielmo IX; each one of the next six documents, named *Jaufre (1-6)*, the *vers* of Jaufre Rudel. The two series were included in the *Known Authors*' box, in files named respectively *Guglielmo* and *Jaufre*. Also in this case, the texts were rotated one by one in the *Unknown Authors*' file, with the result of a full recognition: all the texts attributed to Guglielmo, including the discussed *chansoneta nueva*, and all the texts attributed to Jaufre were recognised. The recognition of 100% of the texts also occurred with the extension of this *corpus* first to nine poems of Raimbaut d'Aurenga, of certain attribution, and then to three authors of his "manner" (Elias de Barjols, Gaucem Faidit, Peire Vidal), with a limited number of texts (four per author). In this last experiment we also added to the texts of *Known authors* a composition attributed to Elias de Barjols (BdT 132,8), for which the attributive *varia lectio* also mentions the name of Gaucelm Faidit; this attribution, in the light of the presented results, should probably be rejected.

Full recognition known on known results were also obtained for the Trouvères poetry, which was stressed with lyrics of Adam de la Halle, Andrieu Contredit, Thibaut de Champagne: in this case I nominated each text with the name of the Trouvère followed by numbers 1, 2, 3 and 4 (therefore adam1, adam2, adam3, adam4, andrieu1, andrieu2, andrieu3, andrieu4, thibaut1, thibaut2, thibaut3, thibaut4). Then I rotated all the documents both in the

Known authors' file, with three compositions per author at a time, and in the *Unknown authors'* file, with one document per Trouvère, obviously the ones not included among the *Known authors*.

In an additional experiment, I tested the method on some authors of the Italian Duecento poetry, in an attempt to verify or falsify the results obtained with the compression method: Amico di Dante (30 sonnets), Bonagiunta Orbicciani (20 sonnets and 5 madrigals), Brunetto Latini (Tesoretto), Guido Cavalcanti (30 sonnets), Cecco Angiolieri (30 sonnets), Chiaro Davanzati (30 sonnets), Cino da Pistoia (30 sonnets), Dante Alighieri (30 sonnets), Dante da Maiano (30 sonnets), Folgore da San Gimignano (30 sonnets), Guittone d'Arezzo (30 sonnets), Monte Andrea (30 sonnets), Rustico Filippi (30 sonnets), *Fiore* (30 sonnets), *Intelligenza* (4500 vv.) and *Mare Amoroso*. In the *Known Authors'* file were placed two documents, nominated with the abbreviated name of the author or of the anonymous work (thus also *Fiore*, *Intelligenza* and *Mare Amoroso*), followed by numbers 1 and 2 (amico1, amico2, bonag1, bonag2, brunetto1, brunetto2, etc.), each containing 10 sonnets or, in their absence (see for example *Tesoretto* of Brunetto Latini or *Intelligenza*), the evaluated syllabic-based equivalence of text amount (approximately 1500 syllables per document).

In the *Unknown Authors'* file were included documents containing another 10 sonnets (or textual equivalence) of each one of these authors or anonymous works, and named like the documents above, but followed by number 3 (amico3, brunetto3, standing for Bonagiunta, and in the absence of sonnets the madrigals were included, thus bonagiuntacan, etc.). The result was 100% "known author on known author" recognition. The three anonymous works were attributed to the authors of the textual portion of the same work included among the *Known Authors* (thus fiore3 was attributed to Fiore; intelligenza3 to *Intelligenza* and mare3 to *Mare Amoroso*).

In the next experiment, *Fiore*, *Intelligenza* and Mare Amoroso were not included in the *Known Authors'* file; they are thus attributed to the authors to be considered as the closest. The result is astonishing since, in front of a "known author on known author" attributive precision of 100%, in the case of the anonymous poems the result is a complete diffraction: in seven cases *Fiore* was attributed to Rustico Filippi, in four cases to Dante Alighieri, in two cases to Cecco Angiolieri and in two cases to Cino da Pistoia; *Intelligenza* was attributed to Rustico Filippi in two cases, in one case to Folgore da San Gimignano, in one case to Guido Cavalcanti and in one case to Dante Alighieri; Mare Amoroso was attributed in one case to Dante Alighieri and in two cases to Rustico Filippi. In my opinion, this result provides the evidence of the fact that the authors of the involved works should be sought outside the group of those included in the *corpus*. I will comment elsewhere the (apparent) discrepancy existing between this result and the result obtained for *Fiore* in the experiments communicated above.

As I already outlined, the method here proposed, in addition to the works of early Romanic literatures, is also being applied to texts of contemporary authors: in collaboration with two scholars of authorship philology, Simone Celani and Paola Italia, I tested it on two interesting and complementary cases, on the one hand some texts of Fernando Pessoa for which there is no clear attribution yet, on the other hand Montale's *Diario postumo* for which serious doubts of apocryphia subsist (at least for a number of poems) (Celani 2005; Italia 2013, 173-196; Celani, *infra*). In both cases, and despite the quite limited size of the analysed textual portions, the analysis of bigrams using *Linear SVM* in *Xtreme Culler* proved itself useful to discriminate authorship, with always quite substantial percentages of "known author on known author" correct attributions; furthermore, interesting results were also obtained in extreme cases such as that of Pessoan heteronyms or that of the probably apocryphal texts of Montale's *Diario Postumo*, generally in confirmation or assistance of the results obtained through downright philological analysis (Canettieri, Italia forthcoming; Canettieri, Celani forthcoming).

Altogether the method of analysis here developed appears to be particularly useful in cases where no vast portions of text are available, for example single poems, and where it is necessary to attribute those to not particularly large groups of authors. Paradoxically, the expansion of textual amount that is available for the analyser, precisely because of the used analyser, might reduce the system's efficiency. Naturally the upper and lower limits beyond which the system loses its efficiency still need to be verified: we know that these limits exist, but their precise identification in relation to the different *corpora* under exam, is another step in the process that will have to bring to systematic exploration of computerised authorship attribution, which still represents, for Romanists, a *terra incognita*.

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ABSTRACT

Methods borrowed from Information Theory are applied to the traditional text criticism. A critique of the raw cladistic methods and an interpretation of the dichotomy-phenomenon are offered. The same methods are applied to 13th century Italian poetry to determine authorship attributions and to verify commonly accepted literary taxonomy. Philology is a human science primarily applied to literary texts and traditionally divided into lower and higher criticism. Lower criticism tries to reconstruct the author's original text and higher criticism is the study of the authorship, style, and provenance of texts. The use of methods borrowed from information theory makes it possible to bring together methodologically some of the sectors of the two fields. The outcome of the experiments in both text criticism and text attribution has been encouraging. In the former, the tests performed on three different traditions have provided results very similar to those obtained by traditional methods requiring a great amount of time. The experiments carried out both on 13th century Italian poets and schools have shown that it is possible to draw texts closer to one another. Furthermore, the method we have used makes it possible to attribute anonymous writings.

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ARTIFICIAL ADAPTIVE SYSTEMS FOR PHILOLOGICAL ANALYSIS: THE PESSOA CASE

1. The Pessoa Archive

Just as Fernando Pessoa offers an extreme example of an open and complex literature, resulting from a heteronymical imagination and constant inclination for expressing the contradictions of human logic and feelings, the same can be said of the Archive that preserves his original manuscripts and which without doubt constitutes an extreme case within the philology of modern and contemporary authors. The features of his writing are in fact well represented in a huge labyrinthine mass consisting of 28,000 documents, which are thematically various and rich in sketches and incomplete works, often written on low quality paper in a hand-writing that is almost always difficult to read. In addition, to crown it all, after his death the papers were organised according to criteria that were at times incongruous and for the most part nullified the arrangements left by the author (Castro 1990; Celani 2005, 2007, 2013).

From poetry to prose, from the essays to the translations, from philosophy to politics, occultism, economics – just to mention some of the subjects that interested him – it seems like there is almost no field of human knowledge that Pessoa did not concern himself with. Hundreds of works have come out of this incredible Archive over the past 70 years, but few of them have been published in a philologically correct form. Even though awareness has grown over the past twenty years about the need to produce critically reliable editions, resulting in a series of volumes that were more conscientious in their attention to the actual material contained in the original manuscripts (I am referring here in particular to the editions published within the project for the national publication of Pessoa's work, being carried out by the "Equipa Pessoa" coordinated by Ivo Castro and published by the Imprensa Nacional-Casa da Moeda publishers of Lisbon), most of Pessoa's works nevertheless continue to circulate in non-critical editions, based either on questionable or not clearly or completely defined criteria. In addition, the challenge faced by the philologist in editing the texts is daunting and it is in part understandable that the series of national editions is proceeding slowly and with extreme difficulty and that the volumes are often doomed to limited circulation among specialists, while the general public prefers slimmer volumes unencumbered with critical notes and commentary (in this sense, the series dedicated to Pessoa co-ordinated by Teresa Rita Lopes and published by Assírio & Alvim publishers of Lisbon have enjoyed great success).

One of the main difficulties presented by Pessoa's works lies in the author's method of composing and conserving his writing. He in fact tended to work contemporaneously on different projects, some of which were written over a span of ten, if not twenty or more, years. Moreover, Pessoa did not often date his sheets. His works, for the most part unpublished during the author's lifetime, tend to be unfinished and present few structural indications; therefore, the problem of identifying objective criteria for their arrangement becomes central. A solution to this problem could be the reconstruction of the documents' chronology, which can in turn be useful in reconstructing the writing process. This was what was done for example with one of the most complex – from the editing point of view as well – of Pessoa's works: the *Livro do Desassossego*, a prose work written in a lyrical style, halfway between an intimate diary, a notebook of reflections, and the narration of the inner thoughts and feelings of a fictional character who would over time take on the definitive name of Bernardo Soares. Given the great disparity of themes and the complete absence of any narrative thread, each editor of the work opted for his own textual reconstruction, following different and often subjective criteria.

The first critical edition focusing on an objective criterion based on the reconstruction of the chronology of the individual passages did not appear until 2010 (Pessoa 2010). The chronology, reconstructed by means of traditional methods of synoptic comparison of the material characteristics of the original documents (Pessoa 2010, II, 530), however, did not produce optimal results: of the 445 passages included in the edition, 316 maintain a very hypothetical dating.

Undoubtedly, the basic criterion is correct, inasmuch as the material features of the originals certainly make it possible to trace the precise stages of the writing, which can be anchored to direct or indirect dates for the purpose of constructing a definite chronology of the literary works. But there are many variables to take into consideration and the process is rather complex. The only way to obtain complete and reliable results is to resort to computerised procedure, which can automatise the crosschecking of the data and obtain wide-ranging results which, if correctly interpreted, can permit a consistent overall view of the different stages and intersections in Pessoa's writing. A first attempt in applying this procedure, based on a sample of 128 original documents from the Archive, has been carried out in the last two years by the ARCHEOSEMA research group (Ramazzotti 2013). The remaining sections of this paper include a description of this work, the results obtained and those which may be obtained in future by extending the dataset to include all the documents in the Pessoa Archive.

2. Basic idea and creation of the dataset

Those who have in some way dealt with the Pessoa Archive for long periods of time will have noticed that in the apparent chaos and random nature of the writing paper used, there are in fact many recurrent elements, ranging from specific formats (size, colour, division into squares, etc.) to headings and watermarks. These elements can provide links among the different parts of the Archive, which make it possible to identify related sections, useful in reconstructing the original stratification of the material. The entropy resulting from the numerous manipulations of the material and the attempts to organise it after the author's death, while eliminating every trace of the original arrangement, nevertheless do not prevent further attempts to reconstruct it. The first step in this direction is to seek to identify all the variables which might be useful in reconstructing the manner and time of the original writing process. For my doctoral thesis, completed in 2004, I worked on an edition of a Pessoa text – an unpublished (and uncompleted) detective story entitled *O Caso Vargas* (Pessoa 2006) – of which I described the material features. The work, consisting of a collection of 128 sheets, was used as a sample *corpus* for the ARCHEOSEMA experimentation.

Each side of every page (for a total of 184 – not all the sheets were written on both recto and verso), identified by its press mark within the Archive, constituted a record in the dataset and was described on the basis of a large number of variables relating to its material characteristics.

The supports on which the texts were written were identified according to parameters such as size (length and width), colour, presence (and typology) of watermarks, headings or other printed text on recto or verso, presence of printed lines or squares, and presence of any cut, folded or perforated parts. The instruments used for writing were on the other hand classified according to type (hand-written, type-written or a combination), use of pen or pencil, and colours used. Finally, all the indications of explicit connections between one document and another have been included, particularly for fragments occupying more than one sheet. In all, as many as 95 variables were indicated for each record (41 for the writing support, 13 for the writing instrument and 41 for the connections among the papers). Starting with the support variables, we can observe that some of the 41 types occur with much greater frequency than others, starting with type 11 (a white sheet cut along one side and measuring 22.1×16.2cm), which occurs in as many as 25 sheets out of 128; type 10 (very similar to the preceding type, being a white sheet cut along one side and measuring 22×16.3cm), which accounts for 16 sheets; type 27 (white sheet measuring 27.4×21.3cm), which includes 12 sheets; and type 19 (which is the back of a form entitled "Anúncios – Tabela de preços", measur-

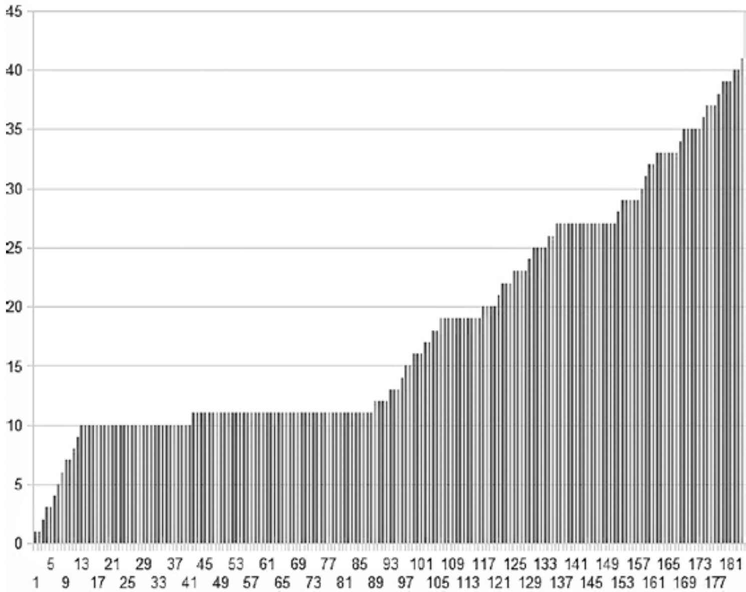

Fig. 1 – Distribution of support types.

ing 26.3×19.6cm) which includes 11 sheets. Thus, half of this collection of papers can be referred to only four types of support (Fig. 1).

With regard to the writing instruments, it is observed that type 5 (pencil) is entirely predominant, and is used in all the papers belonging to support types 10 and 11, in 7 of the type 19 sheets and in 5 of the type 27 sheets (Fig. 2). The matrix obtained from the dataset was then inserted into Intelligent Data Mining developed by Massimiliano Capriotti at the Semeion Research Centre. The dataset was developed according to three different metrics: Linear Correlation (LC), Prior Probability (PP) and Auto-Contractive Maps (Auto-CM). For each of these a Minimum Spanning Tree (MST) was calculated, and represented in the form of a graph using GEPHI v. 0.8.1 software, which made it possible to obtain a concise visual representation of the results. At this point, the data were analysed.

3. Analysis of the data

The graphs in Figs. 3, 4, and 5, based respectively on LC, PP and Auto-CM, were obtained through the application of two main filters: betweenness centrality (which indicates the centrality of a node in the network, obtained on the basis of the number of shortest paths that pass through that

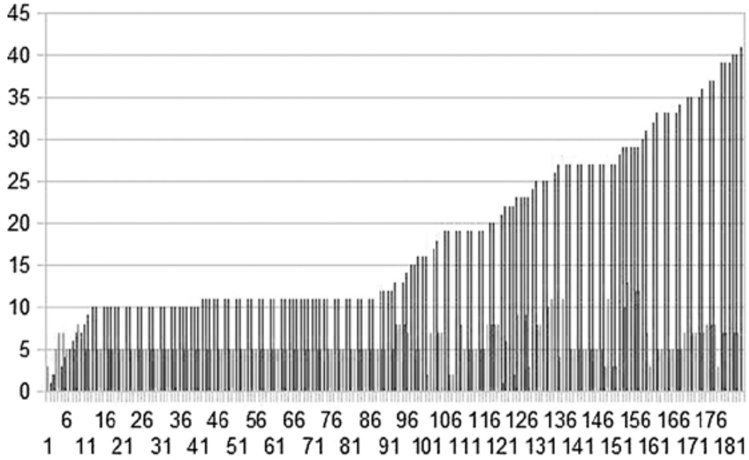

Fig. 2 – Distribution of writing instrument types compared to distribution of support type.

node from all vertices to all others) and modularity (which sub-divides the nodes into a pre-determined number of clusters on the basis of their affinity). Each point (or node) indicates one of the documents which make up the text; the different classes, designated by different colours, identify the different sections of the document set; the lines that connect the nodes indicate the material contiguities among the different records – contiguities which can indicate closeness in conception or drafting of the text. By comparing the graphs produced with the three different algorithms, we can observe that Auto-CM produces a more intelligible result which is in line with the data already known in relation to the content of the individual fragments. Both LC (Fig. 3) and PP (Fig. 4) on the other hand produce graphs which tend to be polycentric and less efficient and which show values in the weights of the connections that are on average low. On the other hand, by analysing the weighted graph obtained with Auto-CM (Fig. 5), it is possible to immediately identify five clusters, of which the first is clustered around the central node while the others are designated by four clearly distinct branches.

The four peripheral clusters correspond, in whole or in part, to the four most frequent types of support. Cluster 2, identified in the upper branch on the left, corresponds completely to support type 11; cluster 3, identified in the lower branch on the left, corresponds almost completely to support type 10; cluster 4, designated by the upper right branch, consists for one third of support type 19; and cluster 5, indicated by the lower right branch, consists for 30% of support type 27. Finally, 35% of cluster 1, which corresponds to the records clustered on the central node, consists of support type 33 (white

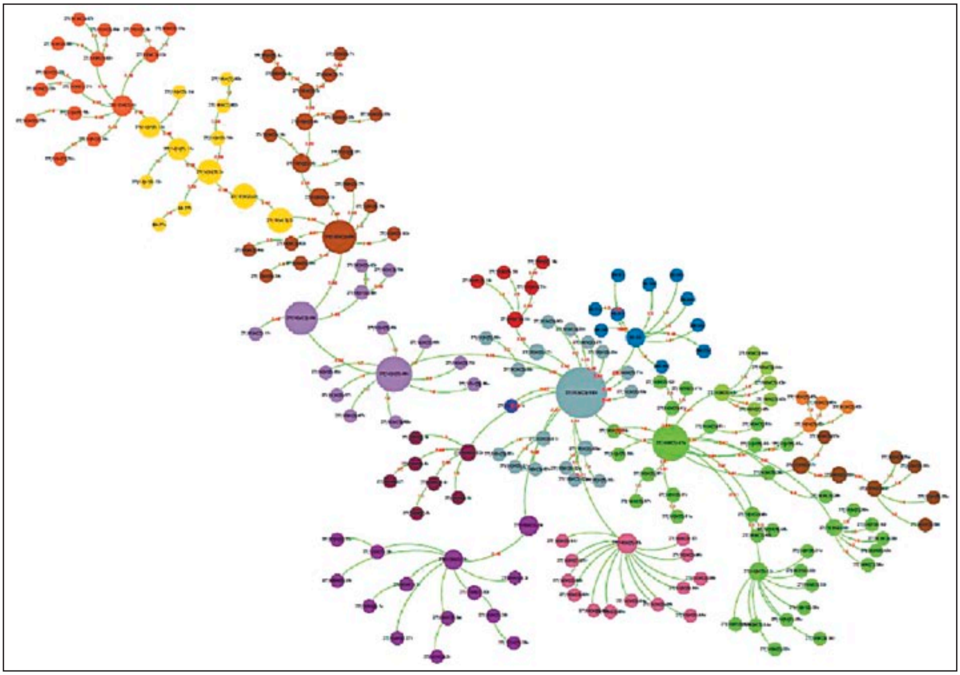

Fig. 3 – LC graph.

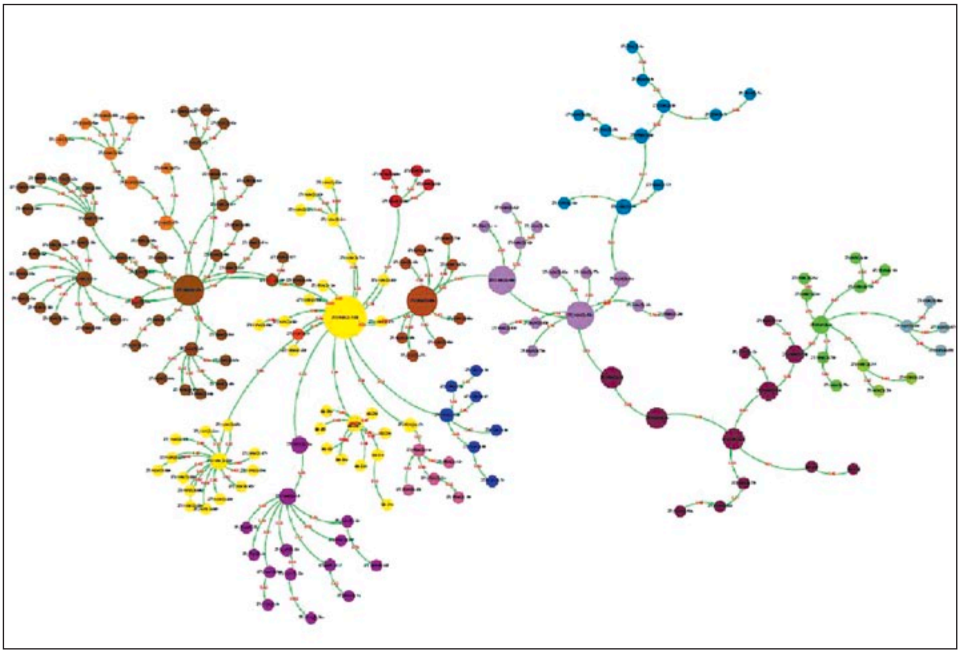

Fig. 4 – PP graph.

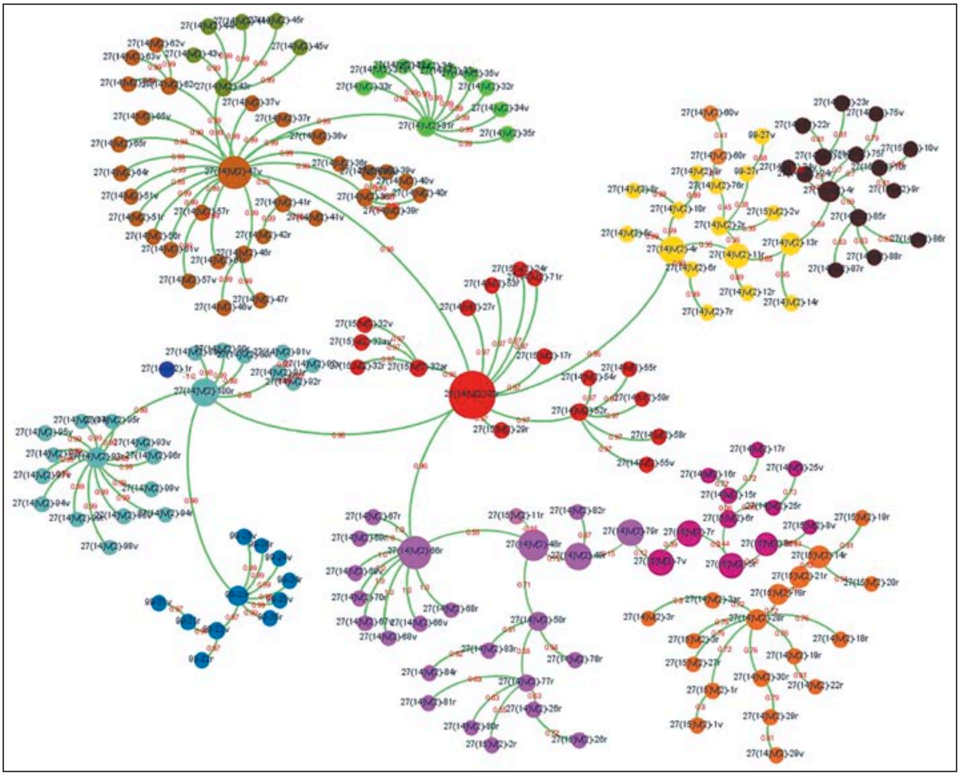

Fig. 5 – Auto-CM graph.

sheet measuring 27.5×21.6 cm) while 23% is made up of support type 12 (folded white sheet headed "F. Caetano Dias – Perito-contabilista" measuring 22.2×14 cm. This was Fernando Pessoa's brother-in-law, managing editor of the magazine «Revista de Comércio e Contabilidade», in which the Portuguese poet was to publish a great number of articles regarding the economic sphere in 1926).

The complete identification between support type and writing type in cluster 2, makes it possible to identify a highly homogeneous block, which is also very cohesive due to the constant force of the connections among its elements (which is always 0.99) and which undoubtedly indicates a clearly distinct phase in the drafting of *Caso Vargas*. The documents are all hand-written in pencil. At this stage, Pessoa would have worked, during very close periods of time, on sections of Chapters 2, 3, 4, 10, 12 and 15.

As already indicated above, another very homogeneous block is cluster 3, consisting entirely of support type 10. The documents are all hand-written with the exception of one. This stage likely corresponds to the writing of parts of Chapters 9 and 12. Cluster 4 on the other hand is less homogeneous; it consists of a central block, which can be identified with support type 19, with a couple of more peripheral segments. The weights of the connections are medium-high, but definitely lower than the average in clusters 2 and 3. The documents are for the most part hand-written. This section, which is more dispersed, consists of writing which is less uniform in content and corresponds to parts of Chapters 2, 4, 6, 8, 10, 12 and 13. Cluster 5 is the most complex and least homogeneous and cohesive of all; the documents are almost equally hand and type-written. A central section consists prevalently of support type 27, while the more peripheral branch presents greater complexity and has much lower average values for the weights of the connections. This cluster includes the writing of sections of Chapters 1, 2, 6, 7, 8, 10, 12, 13 and 15. Finally, cluster 1 appears quite cohesive (with weights of the connections being constant at around 0.97), but less homogeneous than clusters 2 and 3. The documents are all hand-written. The writing of parts of Chapters 2, 3, 7, 12, and 15 belongs to this stage. This description of the five clusters is confirmed in a version of the same graph filtered through the degree parameter (which classifies the nodes according to the number of connections they possess; Fig. 6).

Here it is possible to identify the more cohesive and homogeneous clusters with greater clarity, starting with cluster 2, followed by cluster 3, then 1 and finally by 4 and 5. Let us now try to connect this structure to a likely chronology. *O Caso Vargas* was written during a period of time that goes from the early 1920s (probably after 1923) to 1935, the year of Pessoa's death. The work is mentioned in the famous letter on the genesis of the heteronyms, sent to Adolfo Casais Monteiro on 13 January 1935; even though the title is not mentioned explicitly, it is very likely that the text he is referring to is to be identified as *O Caso Vargas* (Pessoa 1998, 252). These dates were postulated on the basis of information taken directly from the originals, thanks in particular to the presence of headings, watermarks or other texts printed on the sheets used. Such elements make it possible to observe in particular that some of the texts in cluster 5, especially its "peripheral" branch, containing among the material also the fragments which make up Chapter 1 of the work, can be dated to a period after 1923 (the fragments are written on back of a pamphlet by Pessoa titled *Sobre um manifesto de estudantes*, published in April 1923), but probably not much later than that date. Within cluster 2 are found on the other hand passages written during and later than the period 1924-1925 (since they were written on forms for the publication of the magazine «Athena», of which Pessoa was co-editor and which published its five numbers precisely between 1924 and 1925) and others dated to the years between 1926 and 1928, since they were written on sheets with the above-mentioned heading "F. Caetano

Dias – Perito-contabilista”, of which there are other samples in the Archive, some of which have direct dates going back to 1926-1928 (Pessoa 2010, II, 351). Finally, some fragments belonging to cluster 4, found once again in a peripheral branch, can be dated in the year 1931. These are texts written on watermarked sheets headed “Graham Bond Registered”; almost all the texts on the same support present in the Archive, when dated, in fact date back to 1931 (Pessoa 2010, II, 351). There are no traces of dates for fragments belonging to clusters 2 and 3, even though the close connections they have with cluster 1 may suggest that they fall within the central stage of the writing of the text, which is around the second half of the 1920s.

Many of the fragments belonging to cluster 5 in effect include texts that have no direct references to *Caso Vargas*, but contain instead reflections on criminal psycho-pathology of the type that are more characteristic of an essay style. The reflections are completely lacking in any direct references to the events or characters of the work, and were incorporated into it only at a later date. A clear example is sheet $27^{14}V^{2}$-79^{r} in which a hand-written note referring to the character of the murderer is added – most certainly at a later date – to a type-written text tending towards the schematic and regarding a general classification of pathologies which can lead to murder.

The same Auto-CM graph can be visualised in a partially linear manner, reconstructing a possible sequence of the writing stages of the work (Fig. 7). Here cluster 1 is still at the centre, cluster 5 is to the left, cluster 4 to the right, cluster 3 is above and cluster 2 below cluster 1. It thus becomes possible to connect the various clusters (or stages) shown in the graph to an absolute chronology, a procedure that can be extended by increasing the sample subjected to analysis. The evident limitations of the results obtained so far are in fact due to the small size of the *corpus* under study.

4. Conclusions

The Pessoa Archive can be seen as an archaeological site damaged for years by those who delved into it. The huge accumulation of papers still holds traces of the original stratification, which makes it possible to identify many cohesive strata and establish their chronology. Pessoa was in the habit of contemporaneously writing different works, some of which have a time span that is very wide, reaching at times even ten, if not twenty, years. A case in point is *Livro do Desassossego*, whose *trechos* were produced, albeit not uninterruptedly, over a period that goes from 1913 to 1934. But many other works in fact have similar chronologies: we might mention, for example, *Fausto* (1908-1934), *O Caso Vargas* (1923 ca.-1935), *Mensagem* (whose first poems were written as early as 1913, whereas the work itself, as is well-known, was not published until 1934. A date after which in any case Pessoa’s work

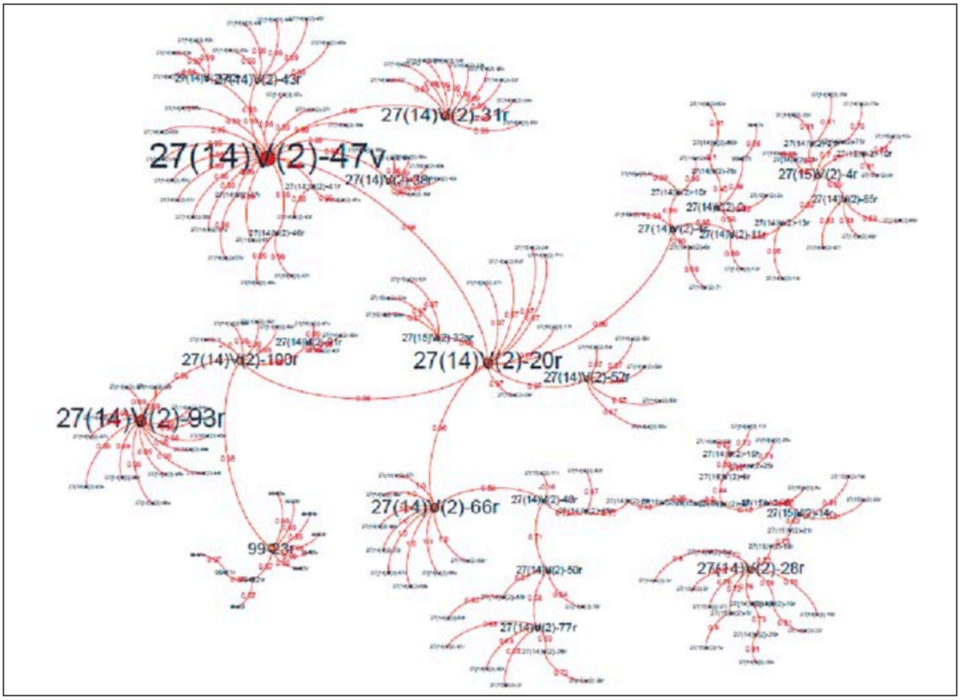

Fig. 6 – Auto-CM graph filtered through the degree parameter.

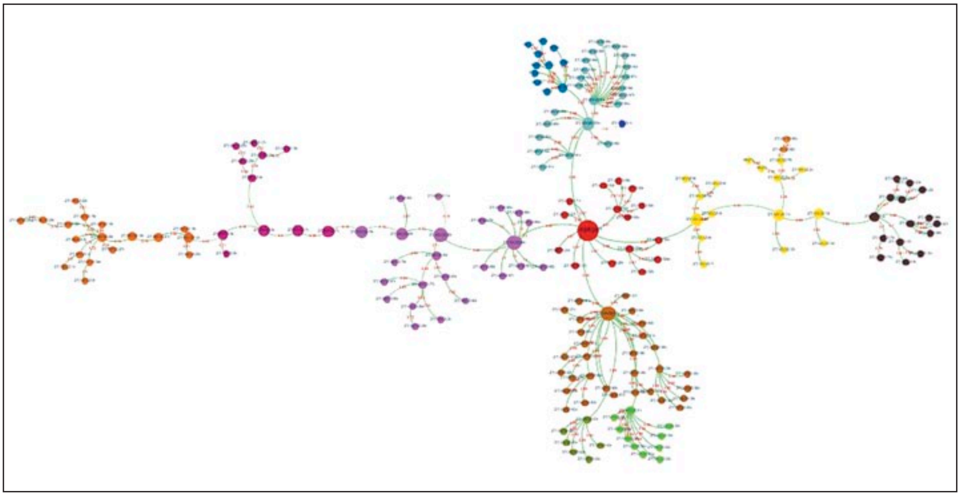

Fig. 7 – A possible chronological visualisation of Auto-CM graph.

on the texts was not completed, as indicated by a printed copy of the work with numerous hand-written variations).

Dealing with this will necessarily require comprehensive study – before any edition is prepared for publication – aimed at gathering up the threads of all the intersections, including those related to content and to the material aspect of the documents in the Archive. Obviously, an endeavour of this scope, carried out on such an extensive *corpus*, will involve a complex process that cannot be achieved with the procedures hitherto adopted: in this sense, a synoptic comparison carried out "by sight", like the one used by Pizarro for *Livro do Desasocego*, besides requiring a long period of time is also doomed to furnish only partial views in which essential elements can escape attention – both in the details or the general aspect.

By subjecting a dataset including the data contained in the entire collection of papers in the Archive to the above-described procedure, it would finally be possible to obtain a comprehensive map of the stratification of Pessoa's writing, in a reconstruction of all the diachronic and synchronic aspects of his creative process, thus illuminating the different stages in the writing of the individual works and placing them within the wider context of his entire literary production. This would be an extremely useful tool for publishing purposes which could permit the construction of a comprehensive scheme for the publication of Pessoa's works, beginning not with the individual works, but with the whole of his literary output. Within such a scheme, each work would have its own specific place and the relations (as well as the not infrequent over-laps) among the different works would be much clearer and more evident. Underlying the overall – albeit incomplete – project of Pessoa's works there is an organised structure, clearly visible despite the apparently fragmentary nature of a great part of his literary output. Pessoa devoted almost as much time to planning as he did to writing his works.

The Archive is full of schemes and lists as well as introductions and prefaces seeking to explain the *ratio* hidden behind his works. Every volume, every collection, every essay is placed within a larger scheme which connects them to other works within a comprehensive and unifying vision. The works of the different heteronyms, like the one of the orthonym, can be read independently of one another, but they take on a further level of meaning only when they are placed alongside one another, in a web where the individual parts are closely interwoven.

The proliferation of heteronyms and literary personalities does not in itself imply a fragmentation of the literary output, but rather a clear attempt at organising and cataloguing the numerous parts of the works, for which each alternative name functions as an explicative label, a space in which to contain elements which in some way are homogeneous.

By carefully reconstructing the connections and homogeneous strata that link the documents present in the Archive, it will finally be possible to read the scheme as arranged through the process of its creation and constitution. But in order to be able to embrace it in its entirety, we need instruments which can concisely represent its complexity without simplifying it. The response to this need may perhaps be found in the utilisation of adaptive artificial networks.

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ABSTRACT

Fernando Pessoa represents an extreme case in the context of contemporary author's philology. The breadth of his legacy, the large number of unpublished works at his death, the disorganisation and incompleteness of his materials and the entropy caused by the early processes of inventory produced an archive, now largely in the possession of the Portuguese National Library, partially refractory to the application of traditional text-criticism methods. This paper will demonstrate, through some application examples, that a careful study of material aspects concerning the originals of the Pessoa archive, made through the use of Artificial Adaptive Systems, will shed new light on the complex and multi-layered writing system created by Pessoa and identify new genetic relationships among his works, useful for the construction of an overall mapping of his literary output.

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ANALYSIS ON THE CUNEIFORM TEXTS OF EBLA. AN EXPLORATORY POINT OF VIEW

1. Introduction

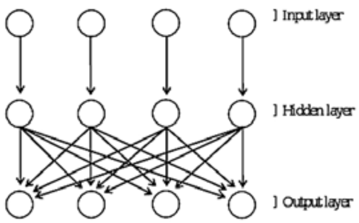
The excavation of the Royal Archives of Early Syrian Ebla, carried out in 1975, represented a truly remarkable discovery for the study of preclassic Western Asiatic cultures. The findings which came to light since that year in a number of rooms located around the Audience Court of the Royal Palace G actually were, and still are, a starting point for a wide range of reflections and works in the fields of economic, cultural and political history. Their noteworthy implications in these fields are probably still far from being exploited in their most heuristic potential. The largest part of the found documents comes from the Great Archive L. 2769, located by the eastern porch of the Court. Most of those documents consist of economic-administrative tablets; some others are school tablets, works of literature, ritual texts, legal documents, or other kinds of texts (Matthiae 1976, 203-209; 1977, 12-13; 1986a, 60-66; 1986b, 46-49; 1995, 222-232; 2010, 118-126; Archi 1996, 66-73).

The tablets may have different appearances and dimensions, depending on their function and content. Large quadrangular tablets contain monthly accounts of assignations of goods; smaller tablets with rounded corners and convex faces bear accounts related to cult activities and tributes; very small roundish tablets can have different contents; very big rectangular tablets contain the lexical bilingual repertoires or literary texts; other very large tablets are yearly or monthly accounts of metals or textiles (Matthiae 1986a, 62-66; 1986b, 50-52; 1995, 227-228; Archi 1986; 1996, 73-75; Ramazzotti 2014). The study here presented investigates the chance to locate elements and clues that can be useful to understand as much as possible the basic features of the structure of cuneiform documents' drafting process. The main target is thus here any feature which could become useful to understand, locate and integrate uncertain, damaged or incomplete texts and which does not emerge from a traditional epigraphic analysis. The group of Eblaite periodic accounts of assignation and transfer of textiles is among the richest ones and is also a class of documents that present a recognisable and linear inner structuring. Because of their number, state of conservation, dimensions, and low degree of complexity, texts related to this category are particularly suitable for an experimental research on the inner structure of the administrative documents produced by the scribes of the Royal Palace G of Ebla.

2. Algorithms adopted and relevant reasons

The approach to the Eblaite administrative documents that has been adopted for this research work is based on observations and viewpoints of linguistic nature, which imply the structural analysis of primary data. Fundamental, in this perspective, is thus not much the content of the documents, nor the economic and administrative phenomena they refer to. It is rather the use and the spatial organisation, within the physical frame of the document, of the cuneiform signs and the contents they express, especially when arranged in more or less long combinations which express specific meanings in terms of administrative accounting. Such an approach must necessarily face the complete absence in scientific literature of works that follow a comparable perspective, and so also the scarce availability of data that could usefully integrate the information that can be found in existing publications or can result from archaeometric explorations. As well known, in the latest years the complicated inner political situation of the Syrian Arabic Republic involves also the impossibility to have access to the collections that are guarded in its museums. This means also the impossibility to collect directly on the artefacts data that were not recorded before. This is clearly a lost opportunity for the enrichment and the strengthening of an investigation like the one that is being presented here, but nowadays available data allow to form a good and coherent starting database. Anyway, for this first experiment available data proved themselves both quite useful and sufficient.

The positions on the inscribed surfaces of the greater components of the document, like sections, as well as those of its minor elements, like single signs, play a constantly central role in the analysis. This is true both for the relative and for the absolute position. The main aim of this strategy is to start an investigation on the logical and perceptive principles underlying the preparation and the drafting of the documents. The coding procedure was based primarily on data related to the syntax and the semantic structuring of both the elementary components (signs) and the larger parts (sections) of a sample of administrative documents containing monthly accounts of textiles (see *infra*). The use of an algorithm like that of the Neural Network "Auto-Contractive Map" (Auto-CM) is precisely due to the basic questions of this investigation and to its linguistic perspective. It is a kind of bottom-up approach which allows to avoid that specific prearranged values or qualities could be attached to any of the observed and coded features. The logics and the coding methods adopted here are thus structurally very similar to those underlying the use of quantitative methods in the study of Mesopotamian glyptic iconographies and use of seals in administration by the author of this



$$[1] \quad E = Min\left\{\sum_{i}^{N}\sum_{j}^{N} u_i \cdot u_j \cdot \sigma_{i,j}\right\}$$

$$[2] \quad E = Min\left\{\sum_{i}^{N}\sum_{j}^{N}\sum_{k}^{N}\sum_{q}^{M} u_i^q \cdot u_j^q \cdot u_k^q \cdot A_{i,j} \cdot A_{i,k}\right\};$$

$$\mathbf{A} = \left(1.0 - \frac{\mathbf{w}}{C}\right);$$

$N =$ Number of Variables (Columns);

$M =$ Number of Patterns (Rows).

Fig. 1 – Structure and algorithm formula of the Auto-CM.

contribution (Di Ludovico 2005, 2010, 2011, 2012, 2013; Di Ludovico, Ramazzotti 2008).

The Auto-CM Network is made of three layers, of which one is the input layer, one the hidden layer, and one the output layer (Fig. 1). Every entry is coded and described in the dataset as a succession of values, each corresponding to a specific observation. The amount of nodes is in each computational layer of the Auto-CM the same of the variables used to describe each entry. The signal is first transmitted from a layer to the following one, and then it is optimised and fine-tuned (Buscema *et al.* 2008), until it reaches the final equilibrium, which corresponds to the energy optimisation. The criteria of similarity and closeness among the entries are fundamental to measure the distances and find the path which requires the minimum energy; such criteria are outlined by the Network on the basis of the inner composition of the datasets. As it will be shown later on, this investigation has been carried out on two datasets, the dimensions of which are respectively 6163×323 and 277×124; the latter was also investigated in its transposed form, 124×277. This means that the relevant Auto-CM processing used, respectively, 969, 372, and 831 total nodes, with 104,652, 15,500, and 77,006 connections between the three layers. A very expressive and useful representation of the processing results is that of the graph tree known as Minimum Spanning Tree (MST), which shows the most economic (in terms of required energy) system of edges that keeps together all nodes. Besides it, one can take advantage also of the Maximally Regular Graph (MRG), which shows the most important cycles, expressing particularly strong and regular connections.

3. Coding of the material

Two different codings were prepared for this investigation, corresponding to two different points of view in the interpretation of structure and content of the texts. A first coding was based on the way cuneiform signs were concretely used: the position of each sign in the tablet was recorded as a place located in a face (obverse, reverse, or minor face), column, section and line. This led to fill up a 6163×323 large matrix expressing the locations of signs in the tablets under examination. This matrix meets the requirements involved by the perspective of investigating the spatial distribution of all signs used within a quite homogeneous *corpus* of documents, so that the structure of their use could be outlined.

The second coding was based on the sections and is justified since each section can be considered a logical unit which bears an inner coherence: in fact, it originated from an independent record. The coding of the sections aims at expressing in a proper way their fundamental traits and any feature having to do with their spatial position within the document which collects them. What is coded is thus both quality and quantity of the mentioned goods, as well as their destination and the date of the transactions. The resulting matrix is 277×124 large, and was thought and investigated in the perspective of the comprehension of the logical frame and spatial organisation of the different kinds of records collected in a monthly account document. In both cases the starting point of the coding adopted is so, unavoidably, the way the surfaces of the tablet were used and internally subdivided. The investigation, however, is centred in the first case on the basic unit that is the cuneiform sign, while in the second case it is centred on the section, which can be seen as a basic aggregate of features related to content and form, rather than a true basic unit.

4. Results of the investigation

4.1 *Sections dataset*

Based on what the MST shows, Tablet T_1 seems quite compact, and only few of its sections are placed distant from its other components (Fig. 2). This phenomenon seems not to be directly related to the (large) dimensions of the tablet, or to the high number of sections it contains. Actually, a little lower degree of compactness can be observed among the nodes referred to the sections of Tablets T_25 and T_19, which form few series of neighbouring nodes and some isolated ones, generally placed in peripheral regions of the graph. The sections which report the monthly total accounts are represented by nodes grouped in peripheral positions. In one group there are the nodes of the sections bearing the AN.ŠÈ.GÚ formula, while in another one we find those of the sections which really close the tablets (Fig. 3). The exception to

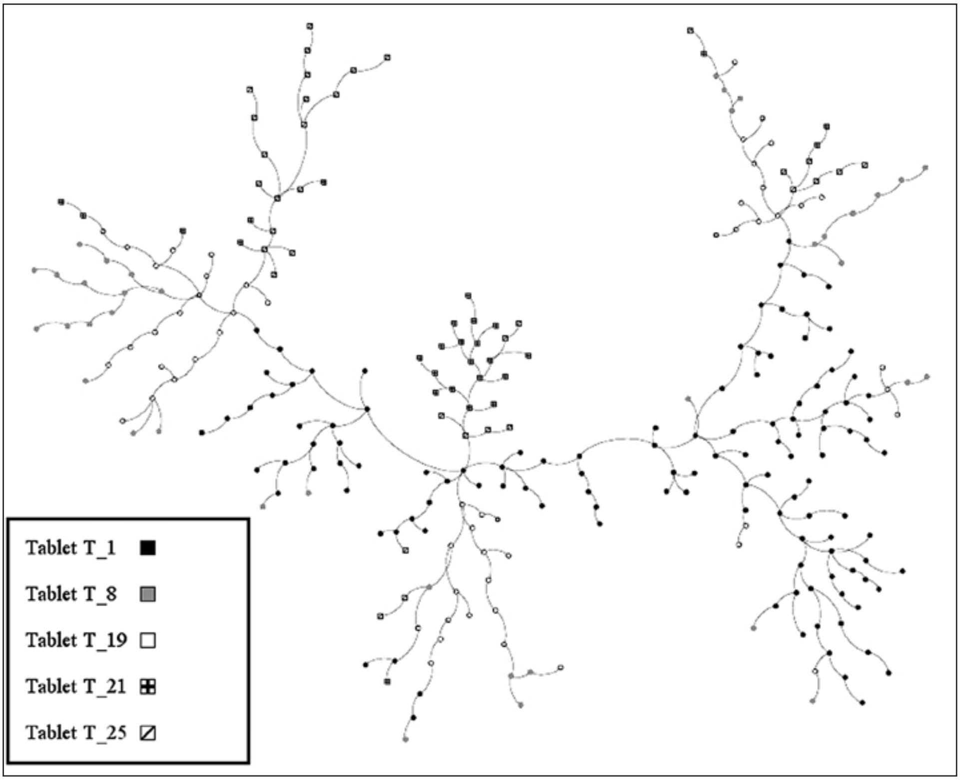


Fig. 2 – MST of the sections dataset: positions in the tree of the tablets' sections.

this is in the neighbouring placement of the two closing sections of Tablet T_1, in the region of the ÁN.ŠÈ.GÚ-sections, but bound to each other by a very weak edge.

In general, a first overview gives also the impression that the arrangement and the quality of the sections on the reverse of the tablets are more compact and homogeneous in comparison to that of those pertaining to their obverse faces. Such an impression would need further confirmation by an enlarged dataset, but it is already signficant that the obverse sections of tablets that are so different from each other as for the dimensions are all represented in the tree as a block of contiguous nodes. This might suggest that the reverse of these documents was generally drafted with a more intense care dedicated to its structural homogeneity, if compared to the obverse. Of the nodes referred to the variables, the one related to the destination of goods is placed in a remarkable position: it has many connections with other nodes and is in

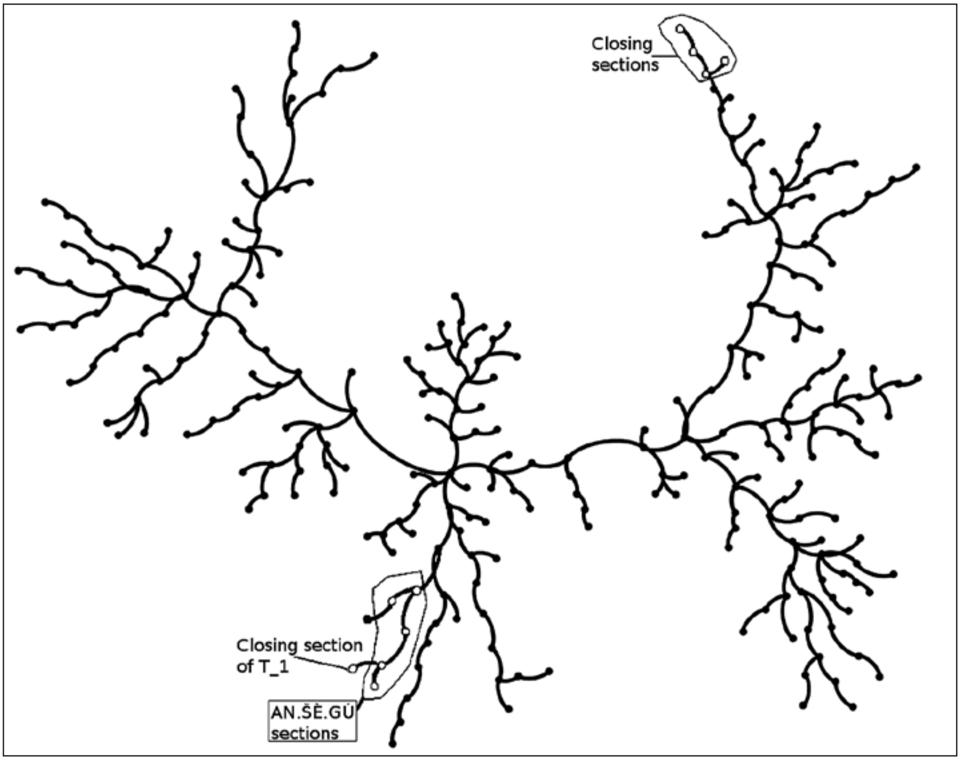


Fig. 3 – MST of the sections dataset: positions in the tree of the sections with the AN.ŠÈ.GÚ formulas and those with the totals.

direct relation to the node which represents the position of the section in the reverse of the document; the latter is also one of the most important nodes, considering the structure of the graph.

Considering the nodes which refer to specific months, the most central in the graph is the one related to the month gi-NI, and very central is also the node which represents the absence of month indication (this is, anyway, a quite obvious phenomenon, which can be similarly detected for the nodes that indicate the absence of traces of erasure). Nodes expressing the identity or quality of the consignee of the goods are in quite peripheral positions, except for the one related to persons that are mentioned with the formula including name and qualification, which is quite central, and directly bound to the node of the position in the obverse face. The kinds of textiles are represented by nodes placed in mid-central regions of the graph. They are especially located close to the node which refers to the position in the reverse face of the tablet.

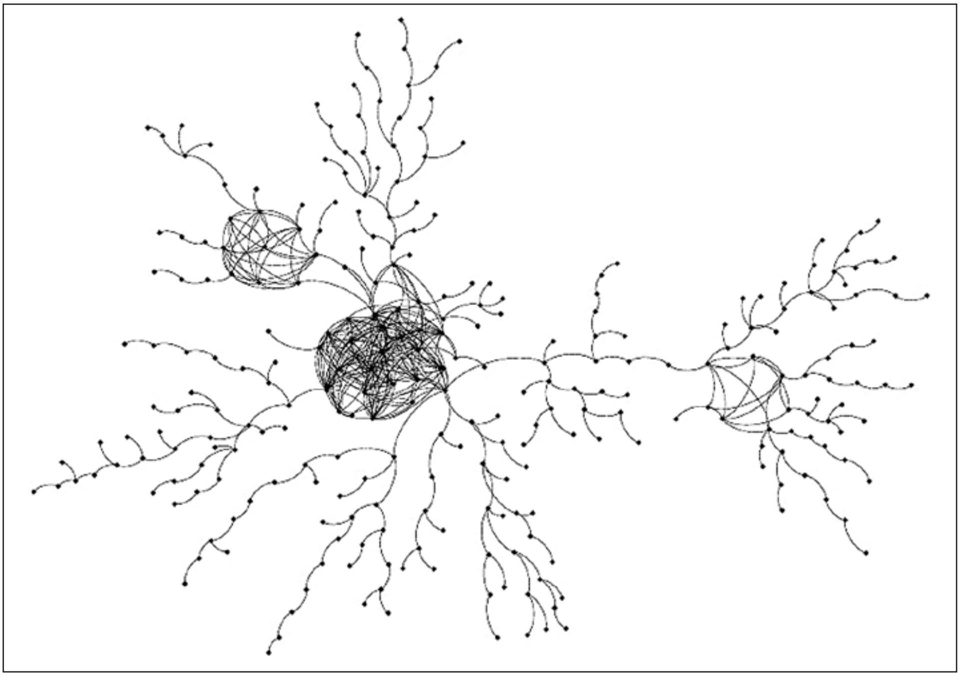


Fig. 4 – MRG of the sections dataset.

Quite peripheral, on the other hand, are the nodes that express in a general form the nature of the assignations, that is, if they concern textiles or other goods.

The relevant MRG shows a similar picture, strengthening the idea that the inner structure of T_1 is particularly compact (Fig. 4). The nodes which refer to its sections form two adjoining diamonds (the term diamond means here any region in the MRG in which the cycles are concentrated, so the whole set of nodes and edges that form that region) and some small branches connected with them. A minor diamond is made of four nodes related to T_19 and three ones related to T_8. As one could have expected, the nodes related to the sections containing the totals are quite distant from the diamonds. The figures emerging from an analysis of the betweenness centrality call the attention especially to the nodes concerning: the position on the reverse of the tablet; the month gi-NI; the assignation of textiles; the type of textile SAL.

A little lower are the figures of the position on the obverse and the type of textile gu-dùl, and much lower are those of the nodes referring to: the assignee, mentioned by name (sometimes followed by his, or her, qualification);

the type of textile gada; the recording, in the section, of the actual destination of the assignation. Furthermore, the average degree analysis shows quite high figures by the nodes relevant to the report of the total monthly amount (introduced with the formula AN.ŠÈ.GÚ) of the assigned goods, as well as to the annotation of the destination of the assignation and to two distinct types of textiles: gada and siki. Meaningful figures which emerge from this analysis are also those related to the mention of the name (that can be followed by the qualification) of the assignee and to the position on the tablet's obverse.

4.2 *Signs dataset*

The investigation on the variables leads to highlight the central role played by obverse and reverse, as well as the peculiarity of the formal structure of tablet T_1. This also emerges from a general observation of the nodes (Fig. 5). The highest figures in betweenness centrality are actually bound to the three nodes, in order (from the highest to the lowest): Obverse, Reverse, and T_1. Although very high, the figures of the latter are anyway much lower than those of the former two. Much lower, but still meaningful, are the betweenness centrality figures that were recorded by the following nodes, all related to the location of the signs (in decreasing order):

1) the section progressive number falls between 16 and 19;
2) column progressive number 7;
3) tablet's line progressive number falls between 145 and 170;
4) the section progressive number falls between 28 and 32;
5) tablet's line progressive number falls between 406 and 476;
6) tablet's line progressive number falls between 171 and 200.

Besides the mentioned ones, 18 nodes related to the position of the line in the tablet and to the section show relatively low figures of betweenness centrality. A null betweenness centrality figure emerges with a large number of other nodes, that is some nodes which could be attached to the same categories of these, as well as all nodes related to columns different from the seventh one, to tablets different from T_1, and to single signs.

The peripheral position of the nodes related to columns, except for that of column 6, seems quite interesting. On the other hand, one has to remark the relatively central location of the nodes expressing the progressive number of the line within the section. Finally, the nodes of the absolute progressive number of the tablet's lines are generally in peripheral positions. The nodes referred to the specific names of the signs are all in the peripheral areas of the graph, and they are distributed in a quite uniform way around those of obverse and reverse, with the only exception of few of them that are placed close to the node of Tablet T_1. It is important to stress here also that the three central nodes are bound to those of the sign names through very weak edges.

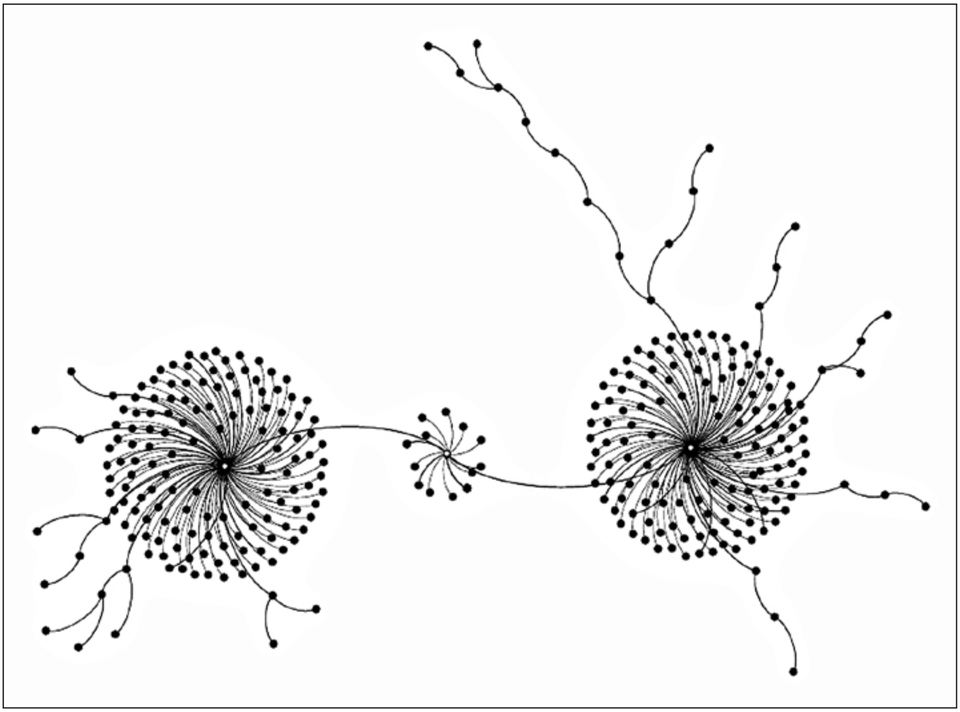


Fig. 5 – MST of the signs dataset. White nodes are related to: position on the obverse (right); Tablet T_1 (centre); position on the reverse (left).

5. Overall interpretation of the outcomes

A first important symptom emerging from this investigation lies in the exceptional cohesion of the group of nodes related to the sections of Tablet T_1, as well as in the quite compact distribution of the groups of nodes referred to those of the other documents. As just shown above, this picture is especially evident in the MRG. Together with the outcomes of the betweenness centrality analysis that have been discussed above, this suggests that the monthly textile account tablets were prepared as a whole, globally, and not just as collections of contents that had been recorded through a relatively limited and short timespan.

This means that they were probably developed and drafted according to new, and typical for them, inner logics. So, the investigation's outcomes allow to think that the monthly administrative tablets dealing with assignations of textiles were very probably not just collections of a number of isolated recordings. In the relevant preparation and drafting works the central idea was probably that of a document which was completely autonomous, besides being of a different kind and following different logics, compared with the smaller records from which it borrowed the contents. It might mean that the textile assignations belonging to a certain month might have been collected in more than one summarising tablet.

This is anyway difficult to be ascertained, since any clues which could permit to identify the year of the tablet's drafting are missing. According to this perspective, the logics on which the drafting of the "summarising" monthly tablet was based could have been grounded mostly on specific inner structuring criteria pertaining only to the monthly accounts, besides the relevance of the single assignations to a same month. The remarkable compactness of the nodes of Tablet T_1 could also be due to its dimensions and to the varied and diversified content of its sections, since of the ones included in this investigation it is also the largest document. In fact, this could have favoured the fulfilment and respect of the inner coherence criteria of the document. If this interpretation is correct, the reason why the other tablets included in this investigation – of smaller dimensions – show a lower inner compactness in the graph is that the relevant content would not be large enough to accomplish quite well the organisational principles underlying the drafting of the monthly document. There is probably no direct relation between the dimension of the document and its inner logical compactness. The latter could be more easily obtained (and observed) in larger documents, but it must be considered primarily in relation to the specific kind of contents and to the quality of the single contributions which were used to build the "summarising" monthly document.

Such a picture seems to be confirmed by data like those pertaining to the structural homogeneity of the different reverse faces of the monthly account documents. This part of the tablet is actually associated to figures that reveal a quite more abstract planning of the sections' arrangement. Of the sections that form the monthly accounts the recording of the totals stand out. In each document they are structured in two parts, distributed through two sections: the first one is introduced by the formula AN.ŠÈ.GÚ, while the second one (which closes the document) mentions the month, the total amount of goods and very often also, separately, the total amount of the gu-mug textiles. In the graph there were two groups, respectively related to the nodes of the AN.ŠÈ.GÚ sections and to those closing the document. These different positions signal the fundamental difference existing between the two last sections of the documents, as well as the – quite evident – qualitative difference between both and all sections that do not report the totals. Data concerning the sections which report the totals are doubtless responsible for an increase of the global complexity of the graph. The nodes relevant to the destination of goods suggest, with their position in the graph, that the recordings of assignations addressed to people or high-level offices of the Eblaite state – like king, queen, or ugula – were deliberately kept distinct from all other transactions, though the monthly recordings collected them together.

The relevant nodes are, actually, all in peripheral positions. This might be a symptom of a basic logical principle of economy and synthesis: in the monthly summarising accounts some occasional assignations were recorded besides the ordinary transactions of textiles, which were very likely the central subjects of those documents. The sporadic assignations of metals and precious goods that are included in some of these documents can be explained in a similar way. The node related to such assignations is in the graph in a peripheral position that can be considered in opposition to that of the nodes referred to the kinds of textiles; the importance of the latter is furthermore highlighted in the graph by the outcomes of the analyses of degree and betweenness centrality (both mentioned above).

6. Current assessments and future perspectives

The investigation presented here allowed to understand and explain concisely and clearly some opportunities to enlarge the research horizons while dealing with a quite homogeneous *corpus* of cuneiform texts. The main issues on which the development of these potentials is grounded are based primarily on the inner organisation and structure of the document, on its global spatial arrangement, and on the relationships existing among the different parts which form, at different levels, the document itself. The administrative document can only bring a fragmentary testimony of the concrete relationship between the space and the written cuneiform sign within a particular cultural context. This relationship was here considered as the shape that a specific sensory framework gave to an administrative attitude. Of this shape, which bears in itself the perceptive complexity of the bureaucratic and management culture of the Eblaite Palace, only shreds and variously disjointed surviving fragments remain to us. The use of models and methodologies based on linguistic principles gives the opportunity to consider under a critical point of view both the perspective adopted in non-philological investigations by the contemporary scientific observer (who, in fact, is hardly involved in studies on cuneiform documents that have neither a philological, nor an epigraphic nature) and the concrete possibility to outline at least partially, starting from the available evidence, the organisational and perceptive dynamics that were actual in ancient times.

In the experimental research that was presented here a sample of not very large administrative texts dealing with textiles transactions has been examined. It was anyway sufficient to test the potentials of the Auto-CM algorithm in relation to the relevant issues. It is especially evident the possibility to glimpse the overall logical project which works as a background for the monthly summarising account documents of the assignation of textiles. The formal framework of these documents is organised on inner compositional strategies that are definitely different from those of a mechanical juxtaposition of contents. Within this general project some peculiarities that increase the global complexity of the document stand out. Examples of such features are some specific kinds of assignations and some atypical sections, like those which report the totals of the monthly account, which have really distinctive features. Currently, investigations like the one that has been showed and discussed here must still face wide-ranging limits and problems.

First, it is important to remark the difficulties in enlarging the sample of documents that can be included in the investigation. On one hand, the intrinsic limits of the epigraphic *corpus* have to be faced: an enlargement of the *corpus* is limited to the nowadays published documents, many of which are fragmentary or very damaged and full of gaps, otherwise it can be accomplished only through occasional and fortuitous findings. On the other hand, a too large *corpus* requires processing machines which could be enough powerful to manage the enormous amount of calculations needed to complete the processing cycle. Besides using avant-garde and appropriate technologies, this second issue could be faced by a refinement of the algorithm's programming.

Another fundamental issue persistently emerges from one of the most ambitious perspectives that can be disclosed by this research course: it is the possibility to prepare a model which could permit to formulate sound integration proposals for the gaps in the documents. For this purpose it is of great importance the problem of fund raising. Resources are needed to start projects in which scholars in the Humanities and mathematicians could give birth to a fruitful and productive dialogue. It is important to find the occasion to elaborate and partly reformulate the algorithms employed, so that the outcoming model would be properly calibrated on the specific tasks and needs of the kind of textual archaeology that is being here promoted. Currently, the results of the preliminary experimental study that has been the subject of this article seem to be definitely encouraging, and foster the expectations for the next steps of this investigation course.

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ABSTRACT

A sample of administrative texts from the Early Syrian state archives of Ebla were coded and processed through the model known as Auto-Contractive Map (Auto-CM). The results of this study led us to focus on some basic issues related to the structure of the Eblaite administrative records which deal with transactions of textiles. This first step is oriented toward the development of a methodology which would allow us to outline some concrete proposals for reconstructing the content of badly preserved tablets.

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KOHONEN SELF-ORGANIZING MAPS TO UNRAVEL PATTERNS OF DENTAL MORPHOLOGY IN SPACE AND TIME

1. Introduction

This review paper relies on two studies we conducted on the classification of human dental morphological data by means of Artificial Neural Networks (ANNs). Analysed samples included Middle Pleistocene to Early Holocene populations across Europe, North Africa and the Middle East. At that time, our research was directed to the classification of a recently discovered dental sample (Tabun cave, Israel) that was compared to a reference database composed of a large number of different samples in order to confirm its belonging to the Neanderthal teeth morphotype (Coppa *et al.* 2007a). The reference database itself was published the same year (Manni *et al.* 2007).

In spite of the very wide application of ANNs in the most diverse scientific disciplines, they have hardly ever been applied to physical anthropology. Prescher, Meyers and Graf von Keyserlingk (Prescher *et al.* 2005) found them suitable for the investigation of a large collection of samples concerning the human nasal skeleton. Corsini, Schmitt and Bruzek (Corsini *et al.* 2005) and Buk, Kordik, Bruzek, Schmitt and Snorek (Buk *et al.* 2012) showed that ANNs make possible a more accurate inference of the age at death, a crucial yet still far from being solved issue in physical anthropology and forensic sciences. Mahfouz, Badawi, Merkl, Abdel Fatah, Pritchard, Kesler, Moore, Jantz R. and Jantz L. (Mahfouz *et al.* 2007) have shown that ANNs yield the best predictive accuracy and classification success rate, among a range of alternative methods, in sex determination according to the dimension of the proximal femur. Another study concerning sex determination, a major issue in anthropology and forensic disciplines, was about the analysis of high-resolution computer tomography images of the femoral patella (kneecap) (du Jardin *et al.* 2009).

To conclude this short list, ANNs have been combined with Geographic Information Systems (GIS) to predict the location of possibly productive fossil-bearing localities (Anemone *et al.* 2011). Our two studies (Coppa *et al.* 2007a; Manni *et al.* 2007) confirm their usefulness in a variety of issues addressed by physical anthropologists, palaeontologists and forensic scientists (classification, prediction) and we advocate their further spread and dissemination in our discipline. This article may be a way to attract the attention of colleagues on ANNs and, in order to provide some insight, we will methodologically review our studies by stressing their advantages over other existing methods.

2. Artificial Neural Networks to classify human dental morphology

In the studies we have mentioned (Coppa *et al.* 2007a; Manni *et al.* 2007), we analysed dentitions of single individuals with the aim to display each of them as a single data point in a kind of multivariate representation. As a consequence, all the traits scored on each tooth of the maxilla and mandible of single individuals were coded as vectors having the components defined by a zero (0), or by a one (1), according to the presence or absence (established on the basis of selected breakpoints) of given morphological tooth traits listed in the *repertorium* of the ASUDAS system (Turner *et al.* 1991; Scott, Turner 1997) (see Fig. 1 for an example). Incomplete dentitions, dental ware and poor conservation often impeded the scoring of all traits, giving rise to missing data descriptors. This is commonplace in the study of anthropological collections of human remains, like bones and teeth, because samples or fragments of the samples can be missing or broken. Teeth, very resistant, are less likely to be broken but are often missing; either they were never recovered in burials or excavations, or they could not be easily attributed to the individual they belong to or – and this also often happens – because they can fall down and get lost in collection repositories. Nevertheless, given the chemical and physical properties of teeth, they are among the elements that best withstand taphonomic processes and they constitute one of the most abundant finds in archaeological sites (Hillson 1986).

The statistical constraints of missing data preclude a number of multivariate analyses, namely Principal Component Analysis, Multidimensional Scaling, Mean Measure of Divergence, Multiple Correspondence Analysis, to mention only the most frequently-used ones. To overcome such limitation, a customary approach in dental anthropology, and one often applied by us in both micro-regional (Cucina *et al.* 1999; Vargiu *et al.* 2009) and macro-regional (Coppa *et al.* 1998, 2001, 2007b, 2007c, 2011; Candilio *et al.* 2010) studies, consists in the merging of different samples into a single population vector by "averaging" available measures in individual samples, either by a mathematical average of real valued traits or by a majority-rule-consensus for discrete measures like the presence/absence ASUDAS system. In this way, the operational units are no longer the single individuals but groups of them, populations, that have no missing components and are statistically tractable (Fig. 2, case A). Another solution, to overcome missing components in vectors, is to consider only those morphological traits that are available in a large number of individuals, meaning that analysed vectors do not correspond to the whole set of traits defined by the ASUDAS system but only to a subset of it.

According to this *modus operandi*, the database is larger when only a few traits are accounted in vectors (Fig. 2, case B), and smaller when more

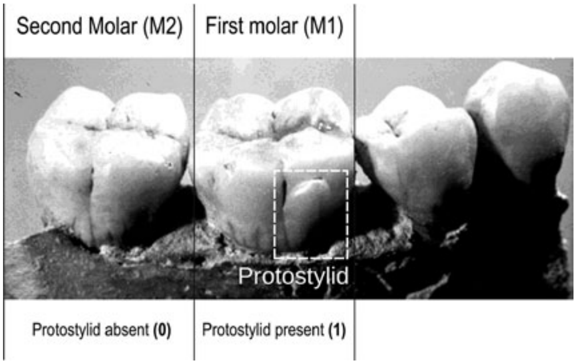

Fig. 1 – ASUDAS scoring system (Turner *et al.* 1991; Scott, Turner 1997) for the description of human dental morphology. Example of a dental trait scored on lower molars (the Protostylid) that can be either present (M1) or absent (M2). Our analyses were made according to 23 traits of this kind, thus giving rise to vectors having 23 binary descriptors.

traits are considered (Fig. 2, case C). In both cases (B and C) the final analysis will be a compromise based on a small number of traits (lack of statistical resolution) or on a low number of individuals (lack of geographical and historical resolution). The "population approach" – though very useful and often adopted – has its limitations as it decreases the sample size and rubs off individual variability. If this is not a major problem in archaeological contexts yielding a large amount of copious anthropological samples, it becomes a serious limitation in less productive sites, as the pooling of the samples "to fill the gaps" may lead to a disharmonic chronology, provenance, or even genetic asset of those included in a population.

To conclude, the analysis by single individuals should be regarded as the optimal one in many paleoanthropological and forensic contexts where the estimation of intra-population variability, in the identification of migrants, and in the identification of different subpopulations, as can be the case – this is just an example – in an ancient battlefield where two very distinct human groups, that had no previous contact before, are buried together in a same site. In such cases, a classification method able to cope with missing descriptors, in other words able to process single individuals, provides a much better insight into the past. This is why we turned to ANNs.

3. Self-Organizing Maps (SOMs) as an application of ANNs

ANNs are machines or software whose architecture is modelled after the brain. They typically consist of hundreds of simple processing units,

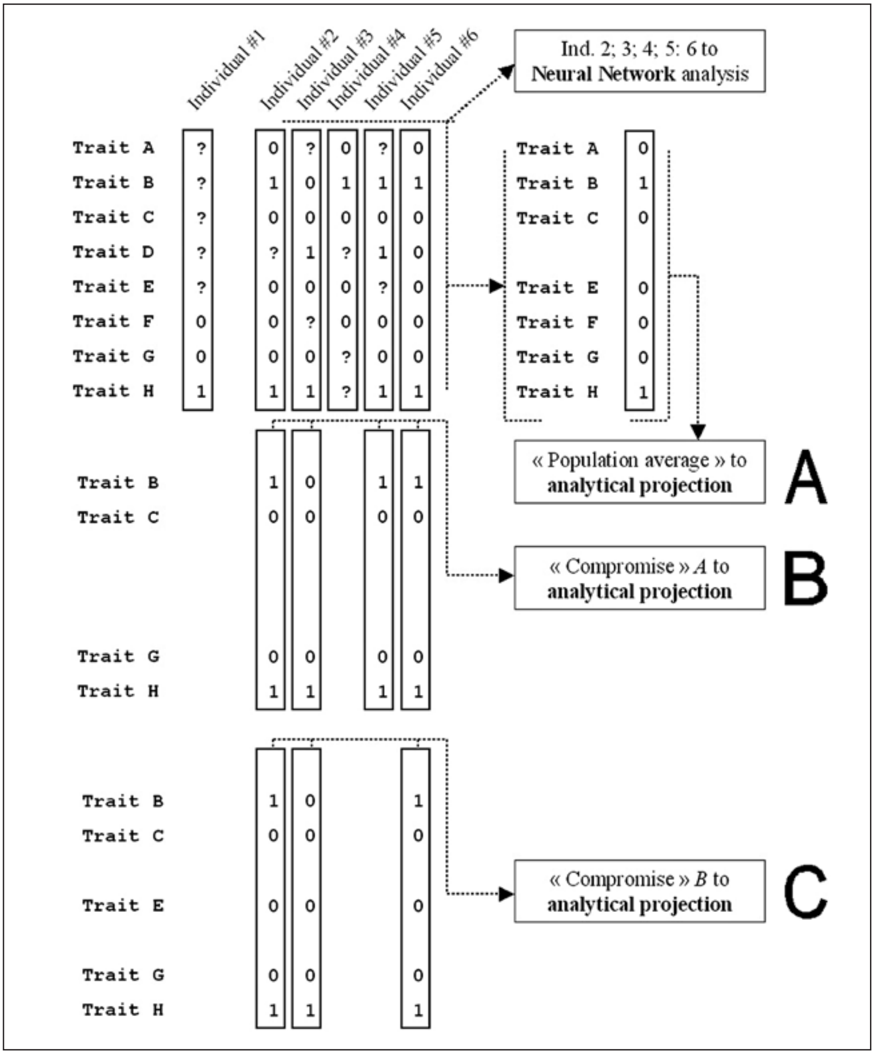

Fig. 2 – Examples of data vectors defined by eight dental traits (A; B; C; D; E; F; G; H). On the top of the figure a dataset of 6 individuals is displayed and the descriptors correspond to the presence (1) or absence (0) of a given dental trait. Missing measures are reported as "?". As all vectors present missing descriptors, we visually suggest the various strategies that are generally adopted to analyze them. In analytical projections (like MDS or PCA), no missing data can be processed, therefore individual samples can be converted in a population vector whose descriptors correspond to a majority rule consensus concerning available descriptors (case A). Otherwise, a compromise between the number of individuals or the number of observations that are kept for the analysis has to be achieved. In B there are 4 individual vectors (#2; #3; #5; #6) with 4 traits (B; C; E; G; H); in C there are less individuals (#2; #3; #6) with more descriptors defining them (B; C; E; G; H). Artificial Neural Network analysis can be used to process the full set. Please note that the vector corresponding to "Individual #1" has been excluded from analyses due to its too many missing descriptors.

which are wired together in a complex communication network. Each unit or node is a simplified model of a real neuron which fires (sends off a new signal) if it receives a sufficiently strong input signal from the other nodes to which it is connected. The strength of these connections may be varied in order to reach different patterns of node firing activity that adjust the network to different classification tasks. In a similar way, the brain contains many billions of a very special kind of neurons that are organised into an intercommunicating network. Typically, each neuron is physically connected to many others and their connections are not merely *on* or *off*, since they can have a varying *strength* which allows the influence of a given neuron on one of its neighbours to be of different intensity (according to its distance from them). Many aspects of brain function, particularly the *learning process*, are closely associated with the adjustment of these connection strengths.

Even if ANN were inspired by the function of biological neurons, many of the software and hardware designs have become far removed from biological reality. At the beginning of their application, ANN were intended as a simulation of neurophysiological processes but, today, they are simply considered to be tools to solve problems. Popular applications concern discrete or real valued high-dimensional input, possibly noisy in the fields of phoneme recognition, image classification or pattern recognition. As an example, we will mention the automatic reading of ZIP codes by distributing machines in major post offices. Camera images of the addresses on the envelopes of the letters are analysed with ANN to recognise the written pattern (ultimately the handwritten ZIP code) and to assign it to reference models (numbers from 1 to 9, including the 0). This example concerns the morphology of written numbers and, after all, our application to teeth concerns morphology as well. ANN can be divided in two categories, *supervised* and *unsupervised*. In *supervised* applications a known dataset is used to train the network, meaning that the final classification of the items is expected to follow an expected categorisation (like the numbers in the ZIP codes).

The ANN can be trained in different ways until the final classification matches the classification expected (learning phase). Once that ANN provide the desired classification of a known database, a new database can be analysed and classified according to the categories (clusters) that the test database yielded in the training phase. Differently, when a desired classification is not known a priori, unsupervised learning has to be preferred. In this latter case there is no expected classification, and the ANN will provide the categorisation that best matches the variation of the data. In this latter case there is no need to use a test database and the data can be entered directly, though the classification output will differ if different datasets are used. In both approaches, the supervised and the unsupervised one, data are clustered on the basis of similarity and correlation criteria.

We adopted a specific version of ANN: Self-Organizing Maps (SOMs) (Kohonen 1982, 1984). SOMs are based on "competitive learning", an adaptive process in which the cells in a neural network gradually become sensitive to different input categories (Kohonen 1982, 1984). SOMs consist of a two dimensional array of neurons, fully connected, with no lateral connections, arranged on a square or hexagonal lattice (the map). Vectors can be different skull measures or, as in the case of this review article, discrete traits of dental morphology. In this process:

1) identical vectors will be mapped at the same position of the map;
2) slightly different ones close to each other;
3) very different vectors will be mapped far from each other.

The visual aspect of data representation obtained by SOMs is somewhat similar to a classical Multidimensional Scaling (MDS) or to a Principal Component Analysis (PCA) plot. SOMs are topology-oriented but the distances between mapped data points do not correspond to a MDS representation (MDS takes a set of dissimilarities – as in a distance matrix – and returns a set of points such that the distances between the points tend to be as close as possible to the dissimilarities), though they describe more accurately the neighbourhood of items (Kaski 1997). For this reason, SOMs should be preferred to MDS or PCA when all the different data (vectors) slightly differ one from another, as is often the case with paleontological data. A type of division of labour emerges in the network when different cells specialize to represent different data points. The SOM maps are divided into an arbitrary number of cells (5×5; 6×6; 7×7; etc.), according to user specifications and, once the analysis is done, each cell (neuron) corresponds to a cluster.

The degree of specialisation is enhanced by the competition among cells: when an input arrives, the neuron that is best able to represent it "wins" the competition and can continue the learning process. If there is ordering between the cells, i.e. when the cells are located on a discrete map, the competitive learning can be generalised. If not, the winning neuron and its neighbours on the map are allowed to learn: neighbouring cells will gradually specialize to represent similar inputs and the representations of input data will become ordered. This is the essence of the SOM algorithm (Kaski 1997). The SOM algorithm is very robust, as it is indicated by the fact that it can go through vectors having missing descriptors (Kaski 1997). With sets of vectors presenting missing descriptor values, only the available values will contribute to the learning process of the map, while the missing values will not. For an effective learning process, it is obviously advisable to process vectors having only a few descriptors missing. Each cell of the map, indexed with *i,* represents a reference vector $\mathbf{m}_i$ whose components correspond to synaptic weights. In the exploration of data, the cell (indexed with *c*) whose reference vector is nearest to the input vector **x**, becomes the winner of the competition between all the different input vectors:

$$c_i = c(\mathbf{x}) = \arg\min \{\|\mathbf{x} - m_i\|^2\} \quad (1)$$

Usually the Euclidean metric is used as a measure of $\|\mathbf{x} - m_i\|^2$.

The winning unit (*c*) and its neighbours adapt to represent the data point even better by modifying their reference vectors towards the current data. The amount the units learn will be governed by a neighbourhood function *h*, which decreases with the distance of all units different from the winning unit on the map. If the locations of cells *i* and *j* on the map grid are denoted by the two-dimensional vectors $\mathbf{r}_i$ and $\mathbf{r}_j$, respectively, then

$$h_{ij}(t) = h(\|\mathbf{r}_i - \mathbf{r}_j\|; t). \quad (2)$$

where *t* denotes time.

During the learning process, at time *t*, the reference vectors are changed iteratively according to the following adaptation rule:

$$m_i(t+1) = m_i(t) + h_{ci}(t)[\mathbf{x}(t) - \mathbf{m}_i(t)] \quad (3)$$

where $\mathbf{x}(t)$ is the data point at time *t* and $c = c(\mathbf{x}(t))$ is the index of the winning unit. In practice the neighbourhood function is chosen to be wide at the beginning of the learning process, to guarantee global ordering of the map, and decreases in width and height, during the learning process. Consisting in the winning selection by equation (1) and in the adaptation of the synaptic weights by equation (3), the learning process can be modelled with a neural network structure where the cells are coupled by inhibitory connections (Kohonen 1993; Kaski, Kohonen 1994). By virtue of its learning algorithm, the SOM forms a non-linear regression of the ordered set of reference vectors into the input surface. The reference vectors form a two-dimensional “elastic network” that follows the distribution of data.

4. Example of classification

As we mentioned in the introduction, the purpose of the analysis (Coppa *et al.* 2007a) was the classification of a new dental sample (TBN-BC7) excavated in the Tabun cave (Israel) that could have been considered a new

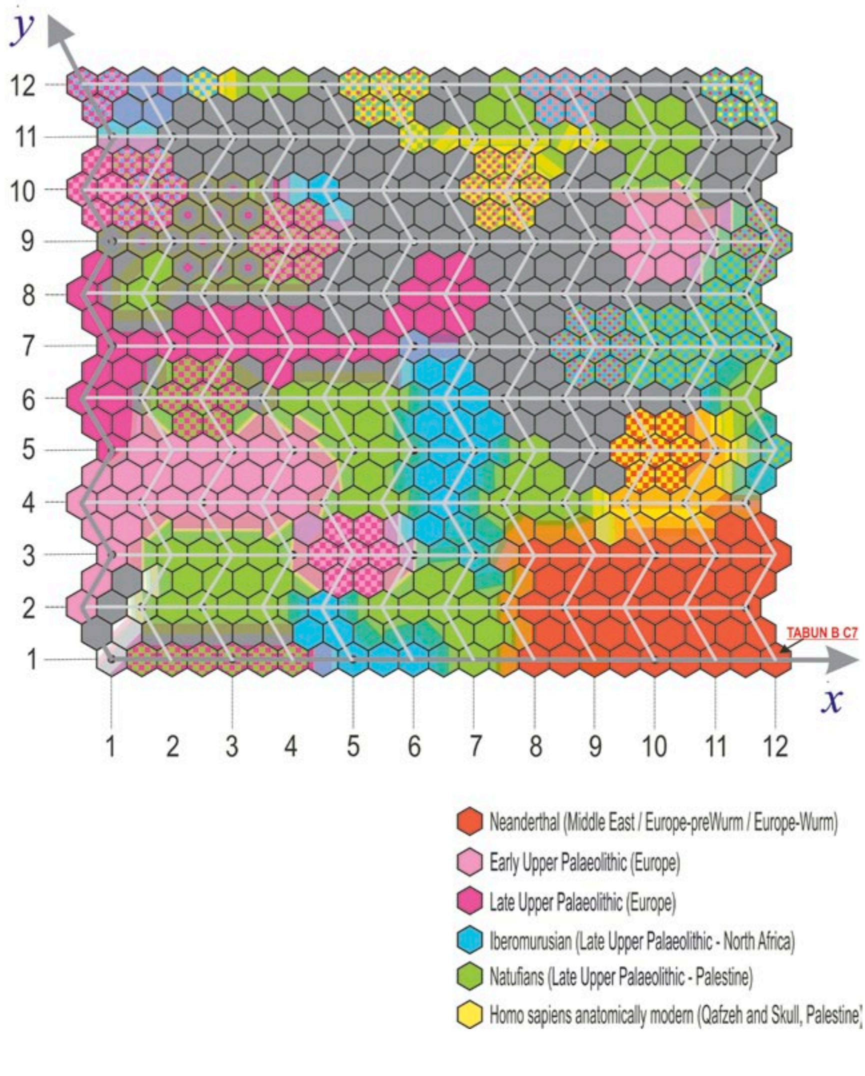

Fig. 3 – Example of a Self-Organizing Map (Kohonen 1982) concerning the analysis of 126 dentitions from different geographic locations and periods. The map is a 12×12 lattice corresponding to 144 neurons. Several samples can be mapped to a same neuron (not shown). We display only the position of the sample Tabun BC7 that falls in an area whose neurons became specialized in the description of the Neanderthal teeth morphotype. The map has been colored according to time periods and geographical areas. Gray cells correspond to empty neurons, meaning that no inputs were linked to them in the classification process (redrawn from Coppa *et al.* 2007a).

Neanderthal specimen, though the issue was debated. Twenty-three dental morphological traits were scored on the Tabun BC7 dentition and compared to a reference dataset of 125 known samples belonging both to Neanderthals and to anatomically modern human specimens from Europe, Middle East, and North Africa, that is covering a large area around the location where the sample TBN-BC7 was discovered. The scoring values of the traits were dichotomised (presence/absence) and a first binary matrix (1/0) was obtained (similarly to the example provided in Fig. 1). When this database was processed with the Self-Organizing Maps algorithm the obtained map (whose size we set at 12×12 cells) displayed an ordered representation (Fig. 3).

Although the upper portion of the map shows an overlapping of dental features for individuals belonging to different periods and samples, this is not the case for Neanderthal samples, which are grouped in the lower right corner of the lattice (in orange). It should be noted that highly divergent samples, in all SOM maps, tend to be mapped at one extreme of the map, as is the case for Neanderthal teeth. The topology and shape of the Neanderthal area suggest that the range of variability of dental features of Neanderthals was different from, and non-overlapping with, the range of variation of the other reference samples and confirmed the belonging of the Tabun BC7 sample to the Neanderthal teeth morphotype.

5. Conclusions

We have successfully experimented the classification properties of Self-Organizing Maps (Kohonen 1982, 1984), an application of Artificial Neural Networks (ANNs) and demonstrated how robust and reliable they are in processing databases heavily flawed by missing data, as it is the case of human dentitions excavated in an archaeological context. ANNs, and SOMs in particular, are capable of classifying the variation through time and space of ancient or degraded human biological material and must be regarded as an invaluable tool to assess ancestry in both archaeological and forensic contexts and to establish the phyletic relations existing between fossil remains. This is why ANNs will be particularly useful to assess if hybridisation occurred between Neanderthal populations, or other species of the genus *Homo*, and populations of anatomically modern humans, and to empirically measure the extent of it (Duarte *et al.* 1999; Di Vincenzo *et al.* 2012; Condemi *et al.* 2013).

The classification that ANNs enable, by making tractable the morphological variation of past human populations at the individual level, will lead to a more accurate depiction of intra-population variation and, ultimately, to a better description of many demographic processes of the past, like migration and admixture. In a wider scale, computational archaeology may also benefit of such neuronal classifications. The computational analysis of artefact features pioneered by Stephen Shennan, like ceramics or basketry that can be dissected in many computationally tractable features (Shennan 2001; Jordan, Shennan 2003), may also benefit of this methodology. In fact, similarly to what occurs in anthropology, artefacts are often incomplete and missing data (pieces, attributes, features). A more widespread application of ANNs will certainly prove much convenient for the anthropological and archaeological community of scholars and we hope to have here contributed to their dissemination.

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ABSTRACT

The paper illustrates how the application of a specific version of Artificial Neural Networks, Self-Organizing Maps (SOMs), enabled a more accurate analysis of human dental morphology. SOMs enable the processing of individual samples (dentitions) because they can cope with missing data. In fact, in archaeological samples of human remains, teeth are often broken or missing making a complete set of morphological traits often impossible to achieve. Other classification methods like Principal Component Analysis, Multidimensional Scaling, Mean Measure of Divergence, Multiple Correspondence Analysis do not handle missing descriptors and incomplete data matrices have to be "filled in", thus leading to a certain approximation in the outcome with a lack of geographical or temporal resolution, as many incomplete samples have to be merged into a virtual one that does not present missing descriptors. Our discussion about the proficiency of SOMs, and ANNs in general, in the exploration and classification of anthropological databases concerning morphology is based on a specific case study, that is the classification of a Neanderthal sample. Through this example we would like to attract the attention of anthropologists and archaeologists to a very flexible methodology that is seldom applied, despite being widely used in many other disciplines.

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INVESTIGATING MESOPOTAMIAN CYLINDER SEALS ICONOGRAPHY BY USING ARTIFICIAL NEURAL NETWORKS. THE ISIN-LARSA PERIOD

1. Models for analysis of figurative Mesopotamian glyptic

Modelling has always been an integral part of the development of archaeology, at least over the past forty years. In the broadest sense, archaeology is the study of the human activity from the past and a model is a simplified representation of reality. As a model does not represent reality, but gives us useful information and allows us to see aspects of the world that we have selected in advance, in a computational model reality is summed up in a few key features, omitting unnecessary details. Human societies in their natural environment can be considered as complex systems.

Such systems consist of many parts that interact with each other and are present in every hierarchy in the universe, from the molecular level to the big planetary systems up to the large-scale structure of the universe. Modelling can help to identify the relationships between items within a complex socio-environmental system in a particular hierarchy. Simulations related to large populations and their non-linear interactions are operations that require a substantial commitment in terms of resources, both human and technological. In recent years, however, the introduction of new mathematical techniques, rapid advances in computing, and tools for modelling have greatly improved the potential of complex systems analysis in archaeology (Ramazzotti 2010, 2013).

Fieldwork and research have always produced large amounts of qualitative and quantitative data. Without some hope to handle their complexity, data derived from non-archaeological research may never be interpreted or published. Therefore archaeologists are able to apply usual statistical methods such as averages and medians, to name just a few, in order to facilitate the reading of the results and produce graphs as histograms and pie charts. In order to adopt a Bayesian method it is necessary to go beyond the classical statistical methods and to use a model-based approach. In each project, researchers need to get an idea of the problem concerned by investigating, examining data and observing how they are distributed. Graphs and histograms are of particular importance in the construction of a model that is very useful and widely used by archaeologists because it allows to simplify the problem and to interpret the results in a clearer and more precise way. Thanks to the modelling of the problem and to the choice of prior evaluations, one can, through the Bayesian theorem, get the information retrospectively. In other words, through the Bayesian approach, *a priori* knowledge and assumptions can be included explicitly in the equations and, thereafter, the interaction between old and new information can be formalised.

Archaeological data are not only a simple record that can be represented, compared, collected, coded, and from which information can be extracted; the record is an integral part of an information process in which the object is only a mean and not the goal of the information flow, influenced by a number of factors in which the context is determined by the dynamics of a cognitive system that auto-organise, so often difficult to decode with "simple" probabilistic and statistical systems that help an interpretation that is more like a snapshot than a tale that unfolds in the plot of time.

Like other fabrics the seals were the subject of both these different lines of research: on one hand, the simple analysis of the different variables linked to the figurative components identified within a scene; on the other hand, the search of connections that overcome this step bringing us to a level of understanding that is as close as possible to the cognitive processes of who made these objects (Ramazzotti 2005). Of fundamental importance are the studies that Camiz and Rova have developed since 1994 through the analysis of a *corpus* of 1247 seals of Jamdat Nasr period (Camiz, Rova 1996, 2001, 2003; Camiz *et al.* 1998, 2003, 2007). The purpose of their research was to obtain an overview of the relationships between different groups of seals studied and classified according to their iconographic features and other factors such as geographical origin, dating and context of discovery.

The methodological basis of this study is based primarily on Multiple Correspondence Analysis up to the elaboration that considers not only the presence or absence of certain iconographic elements, but also the order (as well as their remoteness or proximity) and the way in which they are associated. Their composition can then be examined according to two levels of increasing complexity. The first level is represented by fixed sequences of elements that form small substructures; the second is represented by the composition of the whole image. The third level of analysis is carried out by turning the image into a sequence of symbols or strings. Suitable algorithms are then developed to examine the distance between different sequences. Once a matrix is produced, an analysis of the main coordinates is conducted on the sequences and followed by a Cluster analysis.

Another approach to the problem of the analysis of the seals is represented by Artificial Neural Networks. In short, Artificial Neural Networks (ANNs) are information processing systems that try to simulate in a computer system the operation of biological nervous systems, which are formed by a large number of nerve cells and connections (synapses) between them. Neural networks are based on connective methods consisting of many small units connected together by links weighed and working synchronously and asynchronously. While in traditional computers the data are processed individually and sequentially, in a neural network data work in parallel and are able to handle a considerable volume of information. Artificial Neural Networks come from the need to reproduce typical activities of the human brain, as the so-called associative memory processes, the perception of images, the comprehension of language and the sense-motor coordination.

An artificial neural network attempts to emulate the behaviour of the biological neural network which we usually call the brain, or more accurately to capture the essential features of the processes that allow, thanks to partial knowledge of certain words (patterns), to remember whole sentences or phrases connected to circumstances and places. There are various types of neural networks: the classical classification distinguishes between supervised and non-supervised networks. The first type is characterised by an input and a known output and the weights are updated, during the procedure, according to the wanted output. This procedure is called "training" of the network. The "supervision" consists precisely in knowing the answer you would expect from a given input. A neural network is then able to give consistent answers to inputs that had not been presented in the training phase. The most common network of this type, which is also the most popular, is the multilayer network (i.e. where the nodes are placed in parallel layers, usually 2 or 3, maximum 4); another one is the back propagation network, called after the training algorithm name.

A classic example of a similar network is used for character recognition. A series of characters (usually contained in a square grid) are presented to the network and the network is trained to recognise which characters they are. Then it will be able, given any symbol, to determine which character it "looks like". Non-supervised networks are generally used to perform input classifications, such as the famous Kohonen networks (SOMs – Self-Organizing Maps), which have a wide range of applications (Kohonen 1997). These networks group the inputs into categories consisting of similar inputs (according to certain criteria). A SOM also creates a map of the inputs putting close together similar inputs. A particularly effective application of the use of SOM to the figurative analysis is the study carried out on seals of the Akkadian and Ur III period by Di Ludovico and Ramazzotti (Di Ludovico, Ramazzotti 2008).

Another study that uses a special type of neural networks called Auto-Contractive Maps was published by Di Ludovico and Pieri (2011) and covers in particular cylinder seals of the Ur III period. Auto-Contractive Maps (Auto-CM) are a particular type of non-supervised neural network, developed by P.M. Buscema at the Semeion Research Centre. Those networks are able to trace the natural relationships between variables, highlighting soft and weak links that would escape from a traditional statistical analysis. One can thus highlights the semantic map of the variables identified studying the figurative representation of the seals developing a graph which points out some important connections hardly detectable with other standard probabilistic methods. This method is the one used in the research presented in this paper.

2. The dataset

The first part of this experiment is represented by the creation of a database containing data as homogenous and standardised as possible. The idea of creating a dataset, consisting of a collection of seals and their stamps belonging to period of Isin and Larsa (2000-1750 a.C.), presents not few difficulties that are related to the inherent problems, both the choice of seals themselves and the computer support necessary for the collection of information. Computer tools represent a fundamental instrument to enable researchers to always keep on top of the data, to easily check all the objects collected and to interchange and compare information (Rizza 2006). The structure of the database includes two types of variables: those that can be defined as concrete variables and the abstract ones. The latter are a reflection of our way of understanding the data inside of a quest that has a breath of scientific type. You begin to collect stamps having in mind a theory which is, at that time, only at an initial state, with the awareness of having to make choices that may not be easy and painless, but which are nevertheless inevitable. It is therefore a step forward from the level of ideas to the level of the objective reality which does not always shine~~s~~ for clarity and completeness of the information it contains.

The *corpus* of data must therefore necessarily take into account the following two realities. On the one hand, the seal is a physical object and a vehicle of direct information; on the other hand, the seal can become a *semeion* between two systems of thought that are very distant in time. In this perspective the seal is an object that allows us to move from a reconstructive level to an interpretation level, and a sign that transforms the act of sealing or of possessing the seal itself into a communicative moment for the various socio-cultural aspects that are involved in the study of these objects. Returning to the problem of the selection of seals, the first criterion of inclusion that I chose was determined by the “certainty” of dating.

Regarding the glyptic production and other elements, the period of Isin and Larsa is indeed a moment that raises numerous difficulties in dating (Collon 1986). There are stylistic criteria used for dating, as the presence of intercession scene in place of the presentation scene, or technical criteria as the prevailing use of hematite, a material for the manufacture of the seal, or the development of a new technique of realisation, that can help us, but they cannot give us the certainty of dating which can then fluctuate from the time of the Third Dynasty of Ur to Old Babylonian period. Everything that concerns all aspects of human artistic production may be subject to dating criteria that are not necessarily stylistic, but may involve other levels and mental experience that are not always so mechanically interpretable. This has led to a drastic reduction of the number of items considered, since in most cataloguing works, the Isin and Larsa period is included in the discussion of Early Babylonian period or is considered as the final moment of the Third Dynasty of Ur. Another criterion of selection was the geographical origin, that it was possible to determine being almost entirely the Mesopotamian land.

The seals included in this research are also selected from catalogues able to offer complete information about the materials of their manufacture and their state of wornness, since these information convey crucial observations, which are not exclusive of the seal as an object but may also involve its use and function. The homogeneity of figurative representations led to another important guideline for the selection of the material, as a guarantee of a more timely recognition of formal and aesthetic variables. At the end of this first step of the research, the selected seals were 130. This number permits to reach an acceptable compromise between quality and quantity of inserted objects and, above all, given the number of variables considered for classification, represents an important measure of data. The selected seals and their stamps are from Babylon (51% of the total), from Diyala (43%), and only for three seals the origin is outside Mesopotamia. These three seals were included in the database to offer an example of production outside Mesopotamia. Most of the records examined originate from places that were the subject of excavations especially by H. Frankfort (1955) for the Diyala region and by A. Parrot (1954) for the area of Girsu and Larsa (excavations 1931-1933). Geographical origin, when not explicitly stated, is not determined. Only for 46 seals out of 130 it was possible to establish the exact place of discovery. Other seals come from private collections that have been edited separately, as the Chiha collection (Doumet 1922), or are part of other museum collections as the seals from the British Museum or the seals of the Egyptian Museum of Turin (Bergamini 1987).

The seals have always represented a strong economic attraction for the antiquarian market, for the material which can be invaluable as well as for the ease of transport and also for their possible transformation into a variety of pendants; this explains the significant presence of these objects within private collections. One of the richest collections was bought by the British Museum in 1825 from the heirs of Claudius James Rich (1786-1821), a member of the East India Company resident in Baghdad.

The archaeological excavations can give us only the certainty of the place of discovery, but cannot prove if the seal was actually manufactured in that same place. Even *dating* presents considerable challenges because the seal is a type of object often subject to reuse (re-carving). The reuse of a seal results in a prolongation of its life and in a consequent falsification of the date of its manufacture but it also offers extra details of stylistic and technical nature.

3. Analysis of the iconological representations in the *corpus*

Among interpretative disciplines of history of art, iconology deals with the subject or meaning of the artwork, as opposed to its shape. At a first reading level some primary keys were identified to give us the basic information for the study of figurative representation of the seals of the period examined. Five types of scenes were so identified. The first and prevalent, with a percentage of 45% of the total, is the intercession scene recognised by virtually all scholars as the innovative scene typical of the Isin and Larsa glyptic. The second type of scene is the presentation scene with a percentage equal to 39%, typical of the production period of the third dynasty of Ur, and still considerably used in this period. The third type involves a character in front of the deified King with a percentage of 10%. The fourth kind presents a character in front of deity with a percentage of 5%. The fifth and final type is present on one seal and represents a deity in front of another deity (1%).

We proceed by locating, within every single group, significant elements operating a kind of syntactic deconstruction to discover, for every scene, constituent base elements that present a meaning not changing in contact with other variables (Figs. 1-2). The intercession scene is based on three elements:

1) The interceding deity;
2) The worshipper or another character that is introduced in front of the deity;
3) The object of devotion, which can be either a deified King, or another male or female deity.

These characters interact with each other into a quite standardised compositional scheme: the interceding divinity is represented behind its worshipper with both hands raised; the worshipper follows, with his hands gathered below in front of a deity, which can be standing or sitting and represented with iconographic features that identify it as a deified King or as a deity with no particular signs that could identify it or, on the contrary, as a specific deity of the pantheon. These are the main characters of this type of scene that we can certainly interpret as a cult scene, offering all sorts of variations on the theme. These variations do not change the syntactic level structure of the scene, but are just different interpretations of it, due to reasons that are related to another sphere of investigation leading back to regional type variations, re-carved or engraver's errors unable to interpret it correctly. The increasing number of the actors appearing in the figurative field does not cover the principal level characteristic of this iconology.

Fig. 1 – Intercession scene.

Fig. 2 – Presentation scene.

Some variations in the pattern do not seem to affect the deep meaning of the scenes, as for example in the intercession scene on the seal classified as BM 108777, where three deities intercede; some other variations, like the one on the seal classified as BM 89479, where a woman is represented instead of a worshipper (although the interpretation is uncertain), somehow modify the meaning but not the syntactic structure. On another seal classified as BM 89552 the worshipper is upside down which has been interpreted as linked to a funerary context (Collon 1986).

It is as if in a sentence like: "I eat an apple", simple in its structure with a subject, a verb and a complement, we would add other words as "I eat two apples" or "I eat an apple with gusto": the structure does not change, but the fact of eating two apples provides an extra information that needs decoding however, using other information which often are not available: why two apples? One is too small or the subject is hungrier? Often lacking this depth of information for the seals, our task is to annotate these features in an attempt to shed some light on their meaning that surely exist, because nothing is added to the case especially on an object as the seal so important at a social level.

The second type is the presentation scene. The syntactic structure is similar to that of intercession, but it changes in the spatial arrangement and posture of the protagonists who are always the worshipper, the interceding deity and the divinity or the deified King. The order, however, is different: the goddess interceding before the worshipper that introduces him in the sight of the deity taking him by hand. This type of depiction may have variations on the theme as the previous type with the introduction here of other characters as the dwarf with arched legs and severed head depicted in profile, well attested and in a larger number in the intercession scene. The third type of scene stars a character in front of the deified King. In this case the figure of the interceding goddess is missing. Here, too, the characters in front of the deified King may be more than one and attend other secondary characters.

We are again in front of a cult scene, but the lack of the character who intercedes in front of the deity would have in this case a much deeper meaning that could be related to a different interpretation of the relationship between the character that stands in front of the deity and the deity itself. The absence of interceding deity from the figurative field might lead to think that the worshipper now enjoys a "closeness", a physical relation to the King. This could indicate a direct access of this character to the King, maybe as the holder of a high office within the palace bureaucracy, and its multiplication within the scene may be explained with a father and son (or sons) relationships.

The other two types of scenes examined represent only a variation in the typology of the two main characters involved in the unfolding of the scene, but I nevertheless decided to classify them because the fact that there is a deity in front of another deity, meaning that the character is faced with a deity and not in front of the deified King, perhaps could narrow the field of use of the seal to the templar and not palatial bureaucracy (Winter 1991).

4. The iconographic analysis. The variable elements of the scenes

The analysis shifts, at this point, to the iconographic study of the peculiarities of the variables that do not characterise each typology, either because these are basically constant in all scenes or because they are only occasionally detectable and as such can be considered as elements that enrich the figurative field, but are not decisive enough to modify the interpretation at the semantic level.

Three main classes of variables can be distinguished:

1) Human or divine characters;
2) Animals and hybrid beings;
3) Objects that are not bound to the characters, but are free in the figurative field.

For each of these classes, variables will be examined within the typological characteristics of the scene. The divine figures that can be found within the scene, when they are not replica of the interceding goddess, can offer us considerable enrichment about the iconography of the deities. On the seal BM122834 we can find one deity that presents all the iconographic features of the goddess Ishtar, although in the catalogue I preferred to interpret it more cautiously as a warrior goddess. Some interpretations recognise her as the goddess Shala, the *paredra* of the storm god Adad. The goddess is represented interceding with an advanced foot on the back of a little lion. Torso and face are in frontal position. Two quivers are crossed on her back. Her outstretched hand holds a rod and a ring. Usually she holds, in one hand, a mace with a double headed lion and clutches a curved weapon (harpé) in the other one (Matthiae 2000).

Other deities appear only in two seals: the BM 129500 and BM 102048. The first is in a scene with a character in front of a deity, the second is the so-called nude goddess in an intercession scene. Her identification as a deity is questioned because her attitude with the hands clasped on her belly, in frontal position on a small pedestal or lion cub, would simply identify her as a devout woman connected to fertility cult practices. This type of figure does not seem to appear before 1825 and disappears around 1750. Its presence is linked to a manufacturing type limited to provincial environments and characterised by a linear shape which makes think of a Northern origin (Matthiae 2000).

We shall now proceed to the examination of non-divine figures. One of them is the one defined "the King with the mace", who appears on three seals: BM 102058 (the character in front of the deity); BM 116280 (presentation scene) and BM 89552 (intercession scene). He is represented on the first seal while holding the harpé with one hand and a stick with the other, on the second seal again while holding the stick, and on the third seal naked with a double belt around the waist and a small stick in the hand. Another character has been classified as a "hero" since he is engaged in mythical battles. On the first seal (BM 101972), the "hero" is in frontal position and he is holding a cup from which water gushes; on seal BM 132858 he is represented with a short skirt, standing, while the right hand grasps the rear paw of the lion, his right leg over the animal's head, and finally on the BM 89198 (Fig. 3) in the same position, but naked.

The so-called dwarf from bowed legs is one of the filling characters that distinguish the glyptic production of Isin and Larsa and Early Babylonian period. He occurs in all types of scenes and is represented with both hands raised or with hands folded on the belly, front facing or turned right or left handed, upside down, naked wearing a cap or bald. On two other seals are present the so-called "detached heads", bizarre fill patterns with obscure meaning except perhaps their pictorial value as the representation of the sign *sag*.

Our analysis now focuses on the types of animals and fantastic creatures often represented as human-animal hybrids. The first is the so-called "bull man" recalling mythical fight scenes that characterised the glyptic of the Akkadian period. He is represented standing, grabbing the forelegs of a lion on BM 89303, in heraldic position with another bull man with the arms raised on BM 129500, standing and front facing holding a spear as on BM 89456, or grasping with the right the rear paw of the lion and holding the left paw on the feline's neck as on BM 89026.

Interesting are the representations of all kinds of hybrids between fish and man with all their variations: fish with human head and arms, fish with

Fig. 3 – BM 89198.

human head and cap with crest, fish with human head and fish animal hybrids, the so-called goat fish. All appear individually in the intercession scene except for the goat fish that is present on the BM 129495 seal that represents a presentation scene.

The figure of the hybrids is connected with Enki and has a long iconographic history, from the representation of the seven sages, *apkallu,* civilising heroes sent by Ea to bring culture to the ancient inhabitants of Mesopotamia, until Roman times, especially at the time of Augustus when the Capricorn zodiac sign becomes the symbol of the emperor. Another animal that recurs with some frequency is the lion that appears as a victim of the assault of the "bull man" or as associated to the deity or as standing in the figurative field without a particular relationship with the other characters in the scene. The dog is quite frequent and is often represented as sitting. The inscriptions of the *kudurru* identify him as the symbol of the goddess Gula, who provides for the health of his worshipper and could also recall a symbology which sees the seal as an amulet with apotropaic functions and a lucky charm for the health of its possessor. The monkey is another animal that had excellent luck in this period's glyptic. Always sitting, often found next to the inscription he is also connected somehow with the sun god and associated with the astral symbolism.

The focus now moves on the analysis of the unconstrained variables. These can be further subdivided into symbols that do not have a specific astral meaning and real astral symbols. Astral symbols have an almost ubiquitous presence within the *corpus* of data examined. We can distinguish various types:

1) The crescent moon often represented in top centre of the figurative scene;
2) The star disk with crescent moon;
3) The star;
4) The disk with crescent moon.

The crescent moon is universally referred to as the symbol of the goddess Inanna, and it is often interpreted as linked to a magical and protective sphere. The addition of the sun disk in figurative composition was also seen as a symbol of Eclipse, while for the starry disk, very interesting is the theory advanced by Mehmet-Ali Ataç (2008) that comparing astral symbols connected with the sun in the stele of Naram-Sin with those present in the seals, highlighted the triangular elements inside the iconography of the star disk with crescent moon and distinguishes the ones with straight sides as matching a symbolisation of the light of the sun from those with wavy lines representing the heat of the sun. Mehmet-Ali Ataç interprets this as the symbol of a syncretism between the representation of the Akkadian god Shamash and the worship of the Sumerian goddess Shamash.

5. The training

At this point, after the identification of the variables, we can start the experimental data processing previously identified and selected within the *corpus* of the seals. The data collected in an Access file are exported to an Excel file. The file consists of 160 variables and 130 records and the defined variables are classified in 4 main areas previously identified: iconology, characters (divine and human), animals and symbols. Each main area includes additional subdivisions that add variables of iconographic nature such as the type of clothing worn by a particular character or the posture of animals and characters up to the definition of their location within the figurative field including symbols. The file has been encoded to a text file with the extension .txt. The data so processed have been loaded in the experimental software developed by dr. Massimiliano Capriotti and used by the Laboratory of Analytical Archaeology and Artificial Adaptive System (LAA&AAS), ready for the algorithm processing and weight definition. The parameters chosen for this step were:

1) Input Type: variables.
2) Weight metrics: Auto-Contractive Maps, Linear Correlation, Prior Probability.
3) Auto-CM parameters. Epochs: 100,000, Energy: 0.0001, Learning Rate: 15.

The result is the generation of graphs according to all three types of metrics. To display the corresponding graph we used the open source software GEPHI v. 0.8.1.

6. The MST tree

The next step was the graph visualisation and layout to make it "readable" and the study of the Minimum Spanning Tree resulting from statistical measures already examined in previous chapters. The order in which variables appear is determined by the value set by the Auto-CM matrix. The greater their value, the higher is their representation in this scale that analyses the multiplicity of their connections within the graph. The variables in position number

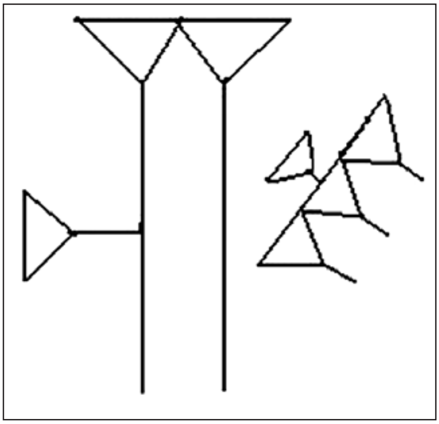

Fig. 4 – *Zibanitu*.

Fig. 5 – BM 11669.

two and three immediately gain our attention and stimulate our curiosity. If we made a simple analysis of occurrences, i.e. how often these variables appear in the figurative field, their position would have been far more modest. Also the graph is susceptible to this sort of trichotomy and expands by following these three branches. The one with hybrid with fish is more peripheral, but the first two are very centrally located. The role represented by a worshipper is certainly a semantically significant character, but the position of the "ball and staff" is definitely a surprise.

Not interpreted univocally, still remains a "mysterious object". Associated with the pot that often accompanies it in the figurative field of the seal, the "ball and staff" is interpreted by some scholars as an object in some way linked to the world of shepherds or connected to the naked goddess and, in this sense, the pot would have performed as a comb and the "ball and staff" as a toiletry item (Collon 1986). For the allocation to the pastoral world the "ball and staff" is indicated as a not better identified subject connected to the carding of wool. The naked goddess does not appear so close in the ramifications of the graph while the pot turns out to be included in the same group. Interesting that the "ball and staff" appears instead associated with many elements linked somehow to the sphere of gifts and divine attributes: harpé and stick, scepter, harpé just to name a few.

The network may suggest something that the only examination related to its mere pictographic representation might not leap immediately to the eyes. More enlightening at this point could be the interpretation of this object as a symbol of the zodiac sign of Libra (Collon 1986). The Libra symbol tied to justice could now justify a central location of this element within an object as the seal, in which justice is seen as the seal of "legality". Certainly striking is the similarity between the iconographic yield of this sign and the cuneiform sign that indicates the scales: the Akkadian *zibanitu* and the later zodiac abbreviation of Libra (During Casper 1997). In this case we could be in the presence of a particular historical moment in which the *zibanitu* has not been "canonised" yet and still suffers from his pastoral tradition tied to a farming calendar and a rendition of the pictographic nature sign (Roger 1998) (Figs. 4-5).

7. The ranking

In the table below, the variables are ranked according to the multiplicity of their connections.

Id	Label	Degree
60	[CHAR]:worsh.1	11
132	[SYMBOLS]: ball and staff1	8
11	[ANIMAL]:hyb. fish1	7
80	[CHAR][POST]:int.H up supp.	4
49	[ANIMAL][POST]: stand	4
44	[ANIMAL][POST]: lie	4
26	[ANIMAL]: bird1	4
140	[SYMBOLS]: drill hole1	4
141	[SYMBOLS]: drill hole2	4
21	[ANIMAL]: monkey1	4
55	[CHAR]:god	4
87	[CHAR][POST]:stand	4
48	[ANIMAL][POST]: sit	4
83	[CHAR][POST]:H right up greet	4
84	[CHAR][POST]:H. left up greet	3
109	[CHAR][ATTR]: animal	3
8	[ANIMAL]: goat	3
37	[ANIMAL][POS]:hight c.	3
33	[ANIMAL][POS]:front	3
28	[ANIMAL]: bull man1	3
9	[ANIMAL]: oyster	3
40	[ANIMAL][POS]:low l.	3
56	[CHAR]: Sun god	3
15	[ANIMAL]: fly	3
79	[CHAR][POST]:Asc.	3
95	[CHAR][CLOTHES] short skirt	3
66	[CHAR] interc.	3
158	[SYMBOLS][POS]: low r.	3
38	[ANIMAL][POS]:low	3
61	[CHAR]:worsh.2	3
98	[CHAR][CLOTHES] naked	3
90	[CHAR][POST]:stand+object	3
76	[CHAR][POS]:front	3
67	[CHAR]: male1	3
58	[CHAR]: w. deity	3
85	[CHAR][POST]:sit	3
150	[SYMBOLS][POS]:right	3
94	[CHAR][CLOTHES]skirt+ lines	3
29	[ANIMAL]: bull man2	2
96	[CHAR][CLOTHES]flound. Skirt+wrap	2
64	[CHAR]: char.1	2
126	[SYMBOLS]: tree	2
45	[ANIMAL][POST]: advan.	2
25	[ANIMAL]: turtle	2
91	[CHAR][POST]:stand offer.	2
47	[ANIMAL][POST]: stood hinds legs	2
31	[ANIMAL][POS]:left	2
70	[CHAR]: king	2
74	[CHAR]: head	2
10	[ANIMAL]:griffin lion h.	2
17	[ANIMAL]: goat fish	2
138	[SYMBOLS]: dates	2
63	[CHAR]:dwarf	2
152	[SYMBOLS][POS]:center	2
118	[CHAR][ATTR]: wedge+ring	2
143	[SYMBOLS]: globes	2
160	[SYMBOLS][POS]: low c.	2
50	[ANIMAL][POST]: upright	2
30	[ANIMAL][POS]:right	2
68	[CHAR]: male2	2
108	[CHAR][HAT]: turban	2
123	[CHAR][ATTR]: scepter	2
71	[CHAR]: K_mace	2
134	[SYMBOLS]: crook	2
159	[SYMBOLS][POS]: low l.	2
24	[ANIMAL]: snake	2
3	[ICO]: Char. In fr. of deif. K.	2
59	[CHAR]: hero	2
131	[SYMBOLS]: staff	2

36	[ANIMAL][POS]:hight l.	2
155	[SYMBOLS][POS]: hight l.	2
157	[SYMBOLS][POS]: low	2
154	[SYMBOLS][POS]: hight r.	2
2	[ICO]: Char. in fr. of D.	2
43	[ANIMAL][POST]: grab	2
13	[ANIMAL]: lion1	2
7	[ANIMAL]: dog	2
153	[SYMBOLS][POS]: hight	2
149	[SYMBOLS]: pot	2
4	[ICO]: Pres. Sc.	2
100	[CHAR][CLOTHES]flound dress	2
57	[CHAR]:Deity	2
52	[CHAR]:goddess2	2
35	[ANIMAL][POS]:hight r.	2
101	[CHAR][CLOTHES] dress+lin.	2
151	[SYMBOLS][POS]:left	2
72	[CHAR]: deif. K.	2
135	[SYMBOLS]: moon cres.	2
105	[CHAR][HAT]:crested cap	2
102	[CHAR][CLOTHES] dress+verti.strip.	2
51	[CHAR]:goddess1	2
62	[CHAR]:worsh.3	2
1	[ICO]: D. in fr.D.	1
130	[SYMBOLS]: post+horn	1
78	[CHAR][POST]:H. up suppl.	1
54	[CHAR]:nak. goddess	1
42	[ANIMAL][POS]:upright	1
137	[SYMBOLS]: star disc+moon cres.	1
5	[ICO]: Interc. Sc.	1
127	[SYMBOLS]: bush	1
20	[ANIMAL]: hedg.	1
46	[ANIMAL][POST]: float	1
65	[CHAR]: char.2	1
6	[ANIMAL]: eagle lion h.	1
136	[SYMBOLS]: disc with moon crescent	1
122	[CHAR][ATTR]: mount m. sh.	1
34	[ANIMAL][POS]: hight	1
16	[ANIMAL]: fish	1
27	[ANIMAL]: bird2	1
113	[CHAR][ATTR]: jag. knife	1
39	[ANIMAL][POS]:low r.	1
93	[CHAR][CLOTHES] flound. skirt	1
22	[ANIMAL]: monkey2	1
14	[ANIMAL]: lion2	1
12	[ANIMAL]:hyb. fish2	1
18	[ANIMAL]: fish+hum. h.	1
110	[CHAR][ATTR]: axe	1
99	[CHAR][CLOTHES]tight dress	1
75	[CHAR][POS]:]up. down	1
23	[ANIMAL]: scorpion	1
112	[CHAR][ATTR]: crook	1
92	[CHAR][POST]:stand roy. post.	1
89	[CHAR][POST]:stand H. up	1
142	[SYMBOLS]: drill hole3	1
103	[CHAR][HAT]: point.	1
119	[CHAR][ATTR]: rod+ring	1
147	[SYMBOLS]: harpÃ©	1
139	[SYMBOLS]: fork	1
120	[CHAR][ATTR]: mace	1
146	[SYMBOLS]: lion scim.	1
116	[CHAR][ATTR]: HarpÃ©+stick	1
125	[CHAR][ATTR]: flow. vase	1
19	[ANIMAL]: frog	1
41	[ANIMAL][POS]:low c.	1
32	[ANIMAL][POS]:center	1
148	[SYMBOLS]: star	1
69	[CHAR]: small figure	1
73	[CHAR]: priest	1
128	[SYMBOLS]: altar	1
117	[CHAR][ATTR]: wedge	1
88	[CHAR][POST]: int.+obj.	1
53	[CHAR]:goddess3	1
144	[SYMBOLS]: spear	1
133	[SYMBOLS]: ball and staff2	1
97	[CHAR][CLOTHES]long dress	1
81	[CHAR][POST]:int. A. left up right back	1
114	[CHAR][ATTR]: cup	1
129	[SYMBOLS]: post	1
77	[CHAR][POST]:H. _Belly	1
156	[SYMBOLS][POS]: hight c.	1
107	[CHAR][HAT]: tiara	1
104	[CHAR][HAT]: cap	1
86	[CHAR][POST]:sit+obj.	1
145	[SYMBOLS]: mace+doub. lion h.	1
82	[CHAR][POST]:int.A. r. back l. H_belly	1
111	[CHAR][ATTR]: stick	1
115	[CHAR][ATTR]: sh. Stick+axe	1
106	[CHAR][HAT]:squared	1
121	[CHAR][ATTR]: sm. vess.	1
124	[CHAR][ATTR]: cur. sword	1

Tab. 1 – The ranking.

8. Betweeness Centrality

With a few tweaks, Between Centrality measure also confirms the same provision of the variables of the graph (Tab. 2).

Id	Label	Betweenness Centrality
132	[SYMBOLS]: ball and staff1	0.665074437
60	[CHAR]:worsh.1	0.651142425
49	[ANIMAL][POST]: stand	0.454661253
80	[CHAR][POST]:int.H up supp.	0.450123398
51	[CHAR]:goddess1	0.442958363
48	[ANIMAL][POST]: sit	0.355624552
28	[ANIMAL]: bull man1	0.349892524
21	[ANIMAL]: monkey1	0.314704243
33	[ANIMAL][POS]:front	0.307300374
87	[CHAR][POST]:stand	0.291218852
109	[CHAR][ATTR]: animal	0.175941406
152	[SYMBOLS][POS]:center	0.171960831
140	[SYMBOLS]: drill hole1	0.16606958
67	[CHAR]: male1	0.153490964
37	[ANIMAL][POS]:hight c.	0.131518191
83	[CHAR][POST]:H right up greet	0.120452193
95	[CHAR][CLOTHES] short skirt	0.109067749
91	[CHAR][POST]:stand offer.	0.107475519
26	[ANIMAL]: bird1	0.097683305
44	[ANIMAL][POST]: lie	0.097205636
11	[ANIMAL]:hyb. fish1	0.086298862
55	[CHAR]:god	0.085900804
98	[CHAR][CLOTHES] naked	0.085502747
30	[ANIMAL][POS]:right	0.073083353
154	[SYMBOLS][POS]: hight r.	0.073083353
100	[CHAR][CLOTHES]flound dress	0.073083353
158	[SYMBOLS][POS]: low r.	0.061778521
85	[CHAR][POST]:sit	0.061778521
17	[ANIMAL]: goat fish	0.061300852
50	[ANIMAL][POST]: upright	0.061300852
135	[SYMBOLS]: moon cres.	0.061300852
15	[ANIMAL]: fly	0.049597962
76	[CHAR][POS]:front	0.049597962
31	[ANIMAL][POS]:left	0.049359127
70	[CHAR]: king	0.049359127
24	[ANIMAL]: snake	0.049359127
3	[ICO]: Char. In fr. of deif. K.	0.049359127
105	[CHAR][HAT]:crested cap	0.049359127
141	[SYMBOLS]: drill hole2	0.037497015
84	[CHAR][POST]:H. left up greet	0.037417403
56	[CHAR]: Sun god	0.037417403
38	[ANIMAL][POS]:low	0.037417403
61	[CHAR]:worsh.2	0.037417403
47	[ANIMAL][POST]: stood hinds legs	0.03725818
68	[CHAR]: male2	0.03725818
13	[ANIMAL]: lion1	0.03725818
149	[SYMBOLS]: pot	0.03725818
101	[CHAR][CLOTHES] dress+lin.	0.03725818
151	[SYMBOLS][POS]:left	0.03725818
8	[ANIMAL]: goat	0.025077621
9	[ANIMAL]: oyster	0.025077621
40	[ANIMAL][POS]:low l.	0.025077621
79	[CHAR][POST]:Asc.	0.025077621
66	[CHAR] interc.	0.025077621
90	[CHAR][POST]:stand+object	0.025077621
58	[CHAR]: w. deity	0.025077621
150	[SYMBOLS][POS]:right	0.025077621
94	[CHAR][CLOTHES]skirt+ lines	0.025077621
126	[SYMBOLS]: tree	0.02499801
74	[CHAR]: head	0.02499801
160	[SYMBOLS][POS]: low c.	0.02499801
123	[CHAR][ATTR]: scepter	0.02499801
159	[SYMBOLS][POS]: low l.	0.02499801
157	[SYMBOLS][POS]: low	0.02499801
2	[ICO]: Char. in fr. of D.	0.02499801
43	[ANIMAL][POST]: grab	0.02499801
7	[ANIMAL]: dog	0.02499801
52	[CHAR]:goddess2	0.02499801
29	[ANIMAL]: bull man2	0.012578616
96	[CHAR][CLOTHES]flound. Skirt+wrap	0.012578616
64	[CHAR]: char.1	0.012578616
45	[ANIMAL][POST]: advan.	0.012578616
25	[ANIMAL]: turtle	0.012578616
10	[ANIMAL]:griffin lion h.	0.012578616
138	[SYMBOLS]: dates	0.012578616
63	[CHAR]:dwarf	0.012578616
118	[CHAR][ATTR]: wedge+ring	0.012578616
143	[SYMBOLS]: globes	0.012578616
108	[CHAR][HAT]: turban	0.012578616
71	[CHAR]: K_mace	0.012578616

134	[SYMBOLS]: crook	0.012578616
59	[CHAR]: hero	0.012578616
131	[SYMBOLS]: staff	0.012578616
36	[ANIMAL][POS]:hight l.	0.012578616
155	[SYMBOLS][POS]: hight l.	0.012578616
153	[SYMBOLS][POS]: hight	0.012578616
4	[ICO]: Pres. Sc.	0.012578616
57	[CHAR]:Deity	0.012578616
35	[ANIMAL][POS]:hight r.	0.012578616
72	[CHAR]: deif. K.	0.012578616
102	[CHAR][CLOTHES] dress+verti. strip.	0.012578616
62	[CHAR]:worsh.3	0.012578616
1	[ICO]: D. in fr.D.	0
130	[SYMBOLS]: post+horn	0
78	[CHAR][POST]:H. up suppl.	0
54	[CHAR]:nak. goddess	0
42	[ANIMAL][POS]:upright	0
137	[SYMBOLS]: star disc+moon cres.	0
5	[ICO]: Interc. Sc.	0
127	[SYMBOLS]: bush	0
20	[ANIMAL]: hedg.	0
46	[ANIMAL][POST]: float	0
65	[CHAR]: char.2	0
6	[ANIMAL]: eagle lion h.	0
136	[SYMBOLS]: disc with moon crescent	0
122	[CHAR][ATTR]: mount m. sh.	0
34	[ANIMAL][POS]: hight	0
16	[ANIMAL]: fish	0
27	[ANIMAL]: bird2	0
113	[CHAR][ATTR]: jag. knife	0
39	[ANIMAL][POS]:low r.	0
93	[CHAR][CLOTHES] flound. skirt	0
22	[ANIMAL]: monkey2	0
14	[ANIMAL]: lion2	0
12	[ANIMAL]:hyb. fish2	0
18	[ANIMAL]: fish+hum. h.	0
110	[CHAR][ATTR]: axe	0
99	[CHAR][CLOTHES]tight dress	0
75	[CHAR][POS]:]up. down	0
23	[ANIMAL]: scorpion	0

112	[CHAR][ATTR]: crook	0
92	[CHAR][POST]:stand roy. post.	0
89	[CHAR][POST]:stand H. up	0
142	[SYMBOLS]: drill hole3	0
103	[CHAR][HAT]: point.	0
119	[CHAR][ATTR]: rod+ring	0
147	[SYMBOLS]: Harpé	0
139	[SYMBOLS]: fork	0
120	[CHAR][ATTR]: mace	0
146	[SYMBOLS]: lion scim.	0
116	[CHAR][ATTR]: Harpé+stick	0
125	[CHAR][ATTR]: flow. vase	0
19	[ANIMAL]: frog	0
41	[ANIMAL][POS]:low c.	0
32	[ANIMAL][POS]:center	0
148	[SYMBOLS]: star	0
69	[CHAR]: small figure	0
73	[CHAR]: priest	0
128	[SYMBOLS]: altar	0
117	[CHAR][ATTR]: wedge	0
88	[CHAR][POST]: int.+obj.	0
53	[CHAR]:goddess3	0
144	[SYMBOLS]: spear	0
133	[SYMBOLS]: ball and staff2	0
97	[CHAR][CLOTHES]long dress	0
81	[CHAR][POST]:int. A. left up right back	0
114	[CHAR][ATTR]: cup	0
129	[SYMBOLS]: post	0
77	[CHAR][POST]:H. _Belly	0
156	[SYMBOLS][POS]: hight c.	0
107	[CHAR][HAT]: tiara	0
104	[CHAR][HAT]: cap	0
86	[CHAR][POST]:sit+obj.	0
145	[SYMBOLS]: mace+doub. lion h.	0
82	[CHAR][POST]:int.A. r. back l. H_belly	0
111	[CHAR][ATTR]: stick	0
115	[CHAR][ATTR]: sh. Stick+axe	0
106	[CHAR][HAT]:squared	0
121	[CHAR][ATTR]: sm. vess.	0
124	[CHAR][ATTR]: cur. sword	0

Tab. 2 – Betweeness Centrality.

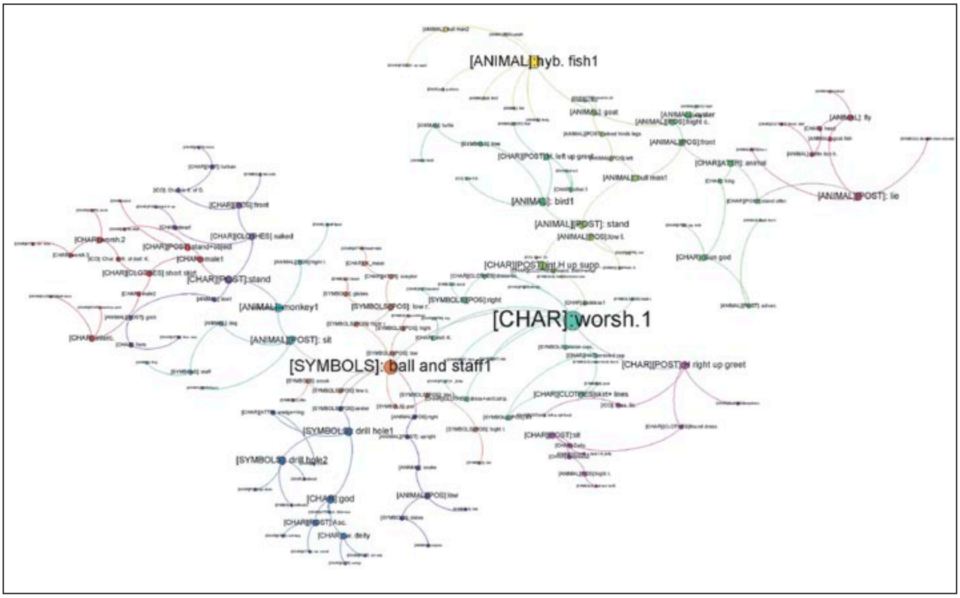

Fig. 6 – The graph.

9. Modularity class

Variables were grouped into 17 classes that are identified with different shades of colours.

Examination of peripheral and central components:

– Peripheral components: devices are isolated groups of variables associated with seals that have peculiarities in the figurative field. Example: Hybrid with fish 1: isolated the seal BM 129500 (Fig. 7) that show in the figurative field a hedgehog, the naked goddess, Bull man, hybrid beings with fish. Green class: A 16968 seal isolated. That presents singular elements too as the tortoise and a stylised tree. Same thing for the seal BM 89392 with the presence of a frog in the figurative field (Fig. 6).

– Central components: connections are very consistent with what we would expect to find in the graph. For the ball and staff refer to the comments of the previous paragraph, while for the worshipper it is definitely not a surprise to see him tied to the deified King to the posture of the interceding goddess and the rising moon; again this is a prototype that does not fall into the singularity, but the usual way of the representation of an intercession scene typical of the period of Isin and Larsa (Fig. 7).

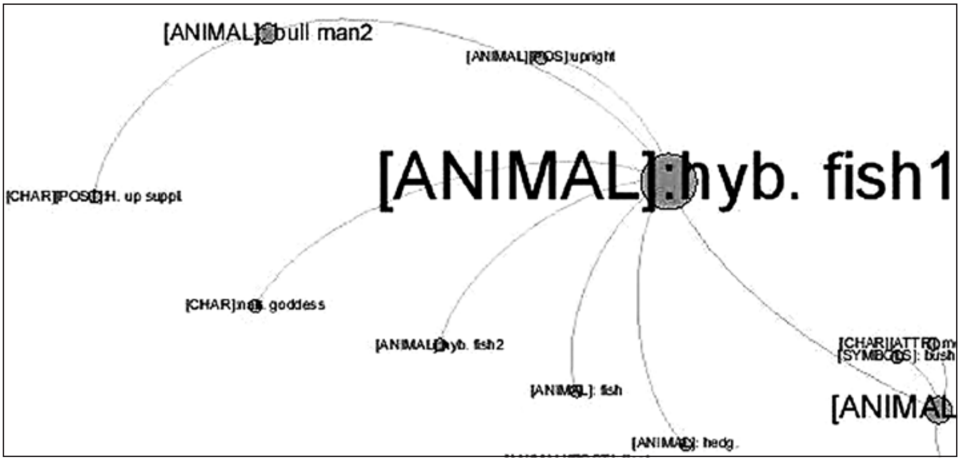

Fig. 7 – BM 129500 in the graph.

Summarising, for the definition of the graph in its more peripheral components the network has detected in these classes "singularities" around which it reconstructed the entire field of a figurative seal, which assumed in this case a prototypical function and meaning, using parameters that go beyond a simple comparative and purely statistical analysis.

10. Conclusion

Altought Neural Networks alone are not the only method of analysis, nevertheless together with a classical approach they can introduce a new way of thinking. They can find logical connections, not affected by the so called western thought, and they are able to find similarities between different cultures without analyzing every single component. Another fundamental element emerging from this analysis is the "wealth" of information that is found in the class of seals of Isin and Larsa, although examined within a limited group of 130 items. The extreme richness of the figurative field and the number of combinations it offers, give us the opportunity to reflect on the presence/absence of any single variable and its persistence in connection with other variables. Small yet great objects which do not "close" as was once their task, but open a thousand doors.

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ABSTRACT

The analysis of a *corpus* of seals belonging to the period of Isin and Larsa, carried out through the use of the Artificial Neural Network Auto-Contractive Maps, allows us to understand the complexity of the relationship of the different elements of the visual domain and its variety. The point of view adopted here is that of reading the iconology and iconography of the so-called "presentation scene" by offering an interpretation that goes beyond the concept of standardised and homogeneous production without any special innovative connotations.

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INVESTIGATING GREEK PAINTED ICONOLOGY BY USING ARTIFICIAL NEURAL NETWORKS. MAENADS AND SATYRS ON ATHENIAN RED-FIGURE POTTERY

Au docteur Jean-Louis Wayenberg, mon papa

1. Introduction

In the history of the studies on Athenian vase-painting, both the identity of the figures named "maenads" and the nature of their interactions with the satyrs have always been subjects of intense debate. The research here presented aims at exploring both the identity of the maenads and their multiple interactions with the satyrs on Athenian red-figure vases, moving from the necessity to formalise and abstract the different and often contrasting elements composing each iconographic picture (Moscati 1984, 1994a, 1995, 72-82).

This chapter presents the preliminary results of an ANN-based analysis applied to a dataset of 114 Athenian red-figure representing 478 figures (maenads and satyrs). Artificial Neural Networks, which have already been applied with encouraging results to different problems in Archaeology and History of Art, represent an innovative tool for the organisation, visualisation and analysis of complex data (Ramazzotti 2010, 128-170; 2013). Technical definitions and data analysis have been conducted by Massimiliano Capriotti; Juliette Wayenberg has conducted the other parts of the present research, thanks to the great support and critical advices of Prof. M. Ramazzotti and Prof. M. Galli.

The interpretation of the huge amount of data has helped highlighting several interesting elements of the iconography of maenads and satyrs. The analysis has been carried out through the study of both the results and the various modern theories expressed by scholars.

2. State of the art

The figures named "maenads" or "bacchae" are variously interpreted by modern scholars. The female companions of the satyrs are generally identified either as maenads (McNally 1978; Keuls 1984; Bérard 1992) or as nymphs (Hedreen 1994; Carpenter 1997) according to their interpretation as human or as mythical figures: the maenads would be the human devotees of Dionysus, while the nymphs would always be mythical figures, personifications of the wild spaces, just as the satyrs. Some scholars simply call them "women" avoiding any further identification as nymphs or as maenads, and considering such rigid distinction between real and imaginary characters inapplicable to the imagery (Lindblom 2011). Maenads have been considered to become hostile to the satyrs' sexual approach at the beginning of red-figure technique and such escalation of the hostility is supposed to reflect the arising of gender tensions in classical Athens (McNally 1978). Some scholars (Hedreen 1994; Neils 2000) argue that the maenads/nymphs would always react with hostility to the satyrs' approaches: in such perspective, the satyrs would sexually harass the maenads but never achieve their goal with them (Neils 2000).

Some other authors interpret the relationships between maenads and satyrs as the reflection of actual Dionysian rituals. The sexual hostility between maenads and satyrs would represent rites of antagonism that offered Athenian women a possibility to relieve from the tensions caused by their everyday subjection to male domination (Keuls 1984). According to Bérard, the erotic features of the satyr-maenad interaction should be considered as the visible part of a Dionysian mysteric ritual including the sexual union of satyr-dressed men and maenad-dressed women (Bérard 1992).

Approaching the subject with a quantitative methodology, Lindblom (2011) suggests that the relationships between the satyrs and their non-identified female companions are multiple and cannot be entirely attributed to the hostility type. The application of descriptive statistics is not unknown in iconographic studies. Though, the further application of advanced Knowledge Management and Knowledge Representation tools and methodologies in the archaeological research is offering new and interesting elements for the understanding of complex systems (Signore *et al.* 2005). Di Ludovico has pointed out the importance of a non-linear approach for another iconographic question (the presentation scenes on Ur seals), in order to recognise the structural relationships existing between the different elements whilst ignoring the interpretations and prejudices of ancient and modern literature (Di Ludovico 2011).

In a previous phase of the research (Wayenberg in press) descriptive statistics and chi-square tests were applied to the iconographic analysis of a selected database in order to redefine the identity of maenads and satyrs by means of their appearance (clothing and hairstyle), and the possible nature of their multiple interactions. The chi-square tests applied to different groups of two variables ascertained the significance of the distribution of many variables among the five analysed periods, highlighting a strong association between iconographic features and time and, in some cases, an evolutionary trend in the iconography of maenads and satyrs. Specifically, on the one hand the appearance of maenads and satyrs and the maenads' reaction to the satyrs' approach were demonstrated to vary significantly among the five analysed periods.

On the other hand, some variables highlighted an evolution in the iconographic definition of the figures, through the diffusion of characteristic iconographic elements, like the presence of the *thyrsus* as a maenadic attribute, the growing amount of non-ithyphallic satyrs and the diffusion of the contemporary Athenian women's wardrobe for the representation of the maenads' appearance, which could be interpreted in terms of an always better distinction between nymphs and maenads on Athenian vases. Indeed, and as seen above, although the rigid distinction between maenads and nymphs is not always certain – and it is not always ascertained that there was, for the vases' users, a clear distinction between them – we have chosen to analyse only the characterised "maenads", interpreted as creations of the imaginary, identified by some precise elements and not specifically defined as mythical characters.

3. Objective of the research and methodology

The framework of maenads and satyrs representations on Athenian red-figure vases is complex and many and contrasting are their modern interpretations. The aim of the present research is to contribute to the research on the identity of the figures represented on vases during a chronological period ranging from the beginning of red-figure technique to the end of the 5th century. BC and to explore the nature of their multiple interactions. Therefore, we have applied innovative ANN-based methodologies to a formalised dataset of statistically selected vases.

3.1 *Dataset*

The inclusion criterion is the presence, on each vase, of at least one satyr and one identified maenad. Maenads are identified by either Dionysian attributes (*thyrsus*, *nebris* or *pardalis*, ivy wreath) or by the presence in the field of the idol of Dionysus or of at least one maenad identified by Dionysian attributes. All the female figures represented without any attribute or accompanied only by satyrs have been considered as possible nymphs and thus excluded from the analysis. The vases were first selected from the Beazley Archive using a period-based statistical stratified method (10% of all vases for each period), based on the postulate that a 10% sample is to be considered statistically relevant, and then organised into a database. The dataset is composed of 114 Athenian red-figure vases, with 96 variables related to both shape (period, painter, function) and figures (appearance, hairstyle, behaviour, relationship).

3.2 *Variables*

Tab. 1 (a, b, c) presents the variables defined for the creation of the dataset, together with their frequency in terms of number and percentage.

The following variables require a specific definition and/or presentation:

1) Vases

– *Shapes*: five classes were defined according to the shape's primary function: drinking shapes (*kylix*, *skyphos*, *rhyton*, *kantharos*); mixing shapes (*stamnos*,

MacroLabel	Variables	Variables Label	Frequency	%
Shape	Serving	SHAPE_Serving	29	25.4
	Mixing	SHAPE_Mixing	31	27.2
	Drinking	SHAPE_Drinking	48	42.1
	Hydria	SHAPE_Hydria	5	4.4
	Lekythos	SHAPE_Lekythos	1	0.9
Environment	Anthropic	ENV_Anthropic	13	11.4
	Natural	ENV_Natural	14	12.3
	Both	ENV_Both	13	11.4
	None	ENV_None	74	64.9
Other Representation	Dionysiac	OT_REPR_Dionysus	44	38.6
	Myth	OT_REPR_Myth	9	7.9
	Daily Life	OT_REPR_Daily Life	39	34.2
	None	OT_REPR_None	24	21.1
Of which: Daily Life	Youth	DLIFE_Youth	18	15.8
	Men	DLIFE_Men	9	7.9
	Women	DLIFE_Women	9	7.9
	Hetaira/e	DLIFE_Hetair*	1	0.9
	Symposium	DLIFE_Symposium	5	4.4
	Theatre	DLIFE_Theatre	2	1.8
	War	DLIFE_War	4	3.5
Period	1	P1	11	9.6
	2	P2	24	21.1
	3	P3	36	31.6
	4	P4	29	25.4
	5	P5	14	12.3
Other Figures	Dionysus	SHAPE_Dionysus	22	19.3

a

MacroLabel	Variables	Variables Label	Frequency	%
Satyrs' Appearance	Naked-Ithyphallic	S_APP_Naked-Ithyphallic	31	27.2
	Naked-Not-Ithyphallic	S_APP_Naked-Not-Ithyphallic	85	74.6
	Citizen	S_APP_Citizen	3	2.6
Satyrs' Hairstyle	Beard	S_HAIR_Beard	110	96.5
	Beardless	S_HAIR_Beardless	10	8.8
Satyrs' Attributes	Thyrsus	S_ATT_Thyrsus	22	19.3
	Nebris	S_ATT_Nebris	16	14.0
	Ivy Wreath	S_ATT_Ivy Wreath	20	17.5
	Vase	S_ATT_Vase	27	23.7
	Branch	S_ATT_Branch	1	0.9
	Animals	S_ATT_Animals	2	1.8
	Torch	S_ATT_Torch	8	7.0
	Instruments	S_ATT_Instr	20	17.5
Satyrs' Behaviour	Quiet	S_BEHAV_Quiet	36	31.6
	Slow Movement	S_BEHAV_SlowMov	34	29.8
	Quick Movement	S_BEHAV_QuickMov	76	66.7
	Music	S_BEHAV_Music	16	14.0
	Wine Service	S_BEHAV_WineService	8	7.0

	Dance	S_BEHAV_Dance	12	10.5
Satyrs' Action	Eye Contact	S_ACT_EyeContact	72	63.2
	Cordial	S_ACT_Cordial	42	36.8
	Grabbing/Grabbed	S_ACT_Grabb	37	32.5
	Approaching/ Approached	S_ACT_Appr	19	16.7
	Extended Hand	S_ACT_ExHand	50	43.9
	Physical Contact	S_ACT_PhysContact	8	7.0
	Procession	S_ACT_Procession	6	5.3
	Symposium	S_ACT_Symposium	5	4.4
	Dance	S_ACT_Dance	11	9.6
	Following/Followed	S_ACT_Foll	34	29.8
	Trying To Release	S_ACT_TryingToRelease	2	1.8

b

MacroLabel	Variables	Variables Label	Frequency	%
Maenads' Appearance	Naked	M_APP_Naked	6	5.3
	Open Chiton	M_APP_Open Chiton	12	10.5
	Citizen	M_APP_Citizen	97	85.1
	Winged Arms	M_APP_Winged Arms	10	8.8
Maenads' Hairstyle	Tied	M_HAIR_Tied	64	56.1
	Untied	M_HAIR_Untied	48	42.1
	Sakkos-Mitra	M_HAIR_Sakkos-Mitra	33	28.9
	With Diadem	M_HAIR_Diadem	34	29.8
Maenads' Attributes	Thyrsus	M_ATT_Thyrsus	106	93.0
	Nebris	M_ATT_Nebris	46	40.4
	Ivy Wreath	M_ATT_Ivy Wreath	26	22.8
	Snake	M_ATT_Snake	19	16.7
	Vase	M_ATT_Vase	20	17.5
	Branch	M_ATT_Branch	7	6.1
	Animals	M_ATT_Animals	15	13.1
	Instruments	M_ATT_Instr	13	11.4
Maenads' Behaviour	Asleep	M_BEHAV_Asleep	8	7.0
	Quiet	M_BEHAV_Quiet	42	36.8
	Slow Movement	M_BEHAV_SlowMov	15	13.2
	Quick Movement	M_BEHAV_QuickMov	67	58.8
	Ecstatic	M_BEHAV_Ecstatic	7	6.1
	Music	M_BEHAV_Music	10	8.8
	Wine Service	M_BEHAV_WineService	11	9.6
	Dance	M_BEHAV_Dance	15	13.2
Maenads' Relationship	Friendly	M_REL_Friendly	58	50.9
	Ambiguous	M_REL_Ambiguous	62	54.4
	Hostile	M_REL_Hostile	16	14.0
	None	M_REL_None	26	22.8
Maenads' Action	Eye Contact	M_ACT_EyeContact	71	62.3
	Cordial	M_ACT_Cordial	40	35.1
	Grabbing/Grabbed	M_ACT_Grabb	36	31.6

MacroLabel	Variables	Variables Label	Frequency	%
	Approaching/ Approached	M_ACT_Appr	19	16.7
	Extended Hand	M_ACT_ExHand	36	31.6
	Physical Contact	M_ACT_PhysContact	5	4.4
	Procession	M_ACT_Procession	7	6.1
	Symposium	M_ACT_Symposium	4	3.5
	Dance	M_ACT_Dance	14	12.3
	Following/Followed	M_ACT_Foll	34	29.8
	Trying To Release	M_ACT_TryingToRelease	23	20.2

c

Tab. 1 – Macro-labels, variables, variables labels, frequency and % of: a) Vases; b) Satyrs, and c) Maenads.

krater); serving shapes (amphora, *chous*, *oinochoe*, *pelike*, *kyathos*); water shape (*hydria*); domestic or funerary shape (*lekythos*).
– *Other representation*: other scenes eventually present on different parts of the vase were divided into mythical (when there is a clear mythical component), Dionysian (with the exclusion of the clearly mythical scenes), daily life (divided into seven daily life categories) and none.
– *Periods*: the five periods were defined according to Cook (Cook 1997): 1 (530-500 BC), 2 (500-480 BC), 3 (480-450 BC), 4 (450-425 BC) and 5 (425-400 BC).
– *Other figures*: presence or absence of Dionysus.

2) Figures

– *Satyrs' appearance*: satyrs can be either naked ithyphallic, naked not ithyphallic, or citizens (when wearing a *himation*).
– *Maenads' appearance*: maenads can be either citizens (when wearing a *chiton*, a *himation* or both), naked, with open *chiton* (when the dress is not entirely covering the legs) or with winged arms (when the arms are covered by the dress' sleeves).
– *Maenads' hairstyle*: tied, untied, with *sakkos* or *mitra* (when the hair are covered), with diadem (other than the ivy wreath).
– *Satyrs' behaviour*: quiet (immobile), slow movement (walking), quick movement (dancing or running); music, wine service, dance.
– *Maenads' behaviour*: asleep, quiet, slow movement, quick movement, ecstatic (defined by violent movements of the head or upper body forward and backward and rotating movements, as stated by Delavaud-Roux (Delavaud-Roux 1991, 2006); music, wine service, and dance.
– *Maenads' relationship*: defines the maenads' reaction to the satyrs' approach, which is either hostile (when the maenad reacts with clear violence to the satyr's approach, by pointing a weapon against him or by violently trying to

release herself from his contact); friendly (when there is a clear non violent interaction between the figures); ambiguous (when the maenad reacts with no clear violence or does not react to the satyr's approach); none (when there is no interaction between the figures).

3.3 *Pre-processing*

The pre-processing consisted in the creation of a unique dataset including both shape and figures variables, by attributing the figures variables to the shapes dataset. Each record corresponds to one vase, and the figures variables register the amount of each variable (appearance, hairstyle, etc.) per vase. We then grouped the variables into labelled macro-variables, and attributed labels to each variable for the data representation (Tab. 1).

3.4 *Type of analysis*

Thanks to Massimiliano Capriotti, we have been able to apply two different levels of analysis to the weighted Minimum Spanning Trees (MST) of the dataset whose weights are based on the Artificial Neural Network Auto Contractive Map (Auto-CM) designed by Prof. Paolo Massimo Buscema at the Semeion Research Center of Sciences of Communication (Buscema, Grossi 2007, 3457-63; 2008, 362-404; Buscema *et al.* 2008a, 481-98; 2008b). All the elaborations here reported were performed with the research software ARCHEOSEMA Lab 1.0, written in C++ for Windows and created by Massimiliano Capriotti for the AA&AAS Laboratory at La Sapienza University of Rome. The MST produced by ARCHEOSEMA Lab are visualised and manipulated by the open-source software GEPHI v. 0.8.1, an interactive visualisation and exploration platform for all kinds of networks and complex systems, dynamic and hierarchical graphs (https://gephi.org/).

A Minimum Spanning Tree is a graph for data classification that is composed of a set of nodes and of a set of undirected edges connecting the nodes. The objective of a MST is to connect all the nodes in an acyclic graph, i.e. by using the minimum amount of connection values (weights), in order to help capturing the key essential information of a dataset without losing any essential information. The nodes of the MST are the entities of a dataset, in this case the variables. Through the weighted MST, we can thus define and display in a graph the network of associations that transform the entities into a structure containing the relevant correlations between the dataset entities, in order to create a coherent picture where the proximity between the entities and the strength of the connections reflect their associations. The two different levels of analysis here presented are:

1) Analysis of the global importance of the variables within the graph, through the analysis of Betweenness Centrality and Mean Weighted Degree of nodes.

The Betweenness Centrality is a measure of the centrality of a node within a graph and, when combined to other statistical measures, of the overall importance of this node for the network. In a weighted network, the edges connecting the nodes are not considered as binary interactions, but they are weighted proportionally to their capacity, influence, frequency, etc., adding another dimension of heterogeneity to the network. The Mean Weighted Degree of nodes is the sum of the connection values per node (rather than the presence/absence of connections). In a graph, the mean weighted degree allows to represent the importance of each node within the network. The analysis of the overall importance of the nodes, applied through the study of the variables with highest and lowest Betweenness Centrality and Weighted Degree values, offers many interpretative possibilities and a huge amount of expected and unexpected results. The expected results are those obtained when the representation of the variables in terms of frequency in the dataset corresponds to their high or low importance within the graph, expressed by their values of Betweenness Centrality and Mean Weighted Degree. The unexpected results are, on the contrary, those obtained when the values of Betweenness Centrality and Weighted Degree do not correspond to the frequency of the variables within the dataset.
2) Analysis of the clusters created by Modularity and of their evolution (persistence and modification) obtained by changing the resolution coefficient. Modularity is a clustering tool that identifies, within the network, different clusters (or "modules"), associating each node of the network to one of the modules. Clustering is a mathematical process in which different elements in a particular network are grouped together based on certain similarities between the different elements. Thus, Modularity helps to identify sub-networks within the network and to display in a graph how the nodes of a network are forming self-contained modules. A modularity value of 1 would suggest that the nodes are perfectly connected to other nodes forming self-contained clusters, while a value of 0 would suggest the opposite. The Modularity analysis allows to view the cluster to which each node has been associated with. In order to create the clusters, it is necessary to set the parameter of the resolution coefficient, from the default value of 1:0 to growing values providing a smaller amount of bigger clusters. The MSTs obtained with Modularity for a resolution coefficient growing from 1 (default) to 6 will be presented. The analysis of the differences and/or similarities in the evolution of the clusters obtained with different resolution coefficients furnishes different interpretative information. The analysis of the nodes with the highest values of Mean Weighted Degree within the clusters defined by the different Modularities consents to measure the local importance of the nodes as the centres of the connections of each sub-network. Therefore, the analysis of the weighted degree within the clusters consents to evaluate the local importance of a node in a defined sub-structure.

4. Results of the data processing

4.1 *The importance of figures as central nodes*

Figs. 1 and 2 present respectively the Betweenness Centrality and the Mean Weighted Degree of nodes of the variables. The central nodes are here graphically presented. Tab. 2 presents the ten highest values of Betweenness Centrality (a) and Mean Weighted Degree (b), respectively. Six variables relating to the figures' appearance and behaviour are present among the highest values of Betweenness Centrality and Mean Weighted Degree. They are, for the satyrs, the beard (S_HAIR_Beard: 223 items, 93% of all satyrs), which is also the centre of the network, the appearance "naked not ithyphallic" (S_APP_Naked-Not-Ithyph: 166 items, 69%) and the "quick movement" behaviour (S_BEHAV_QuickMov: 138 items, 58%). Those are all expected results since they reflect the frequency of the variables within the dataset. For the maenads, the highest values belong to the citizen appearance (M_APP_Citizen: 196 items, 82% of all maenads), the action "dance" (M_ACT_Dance: 25 items, 10%) and the untied hair (M_HAIR_Untied: 89 items, 37%). Two unexpected results are: 1) the absence, among the highest values, of the tied hair (M_HAIR_Tied: 96 items, 40%), and the presence, instead, of the slightly less frequent untied hair; 2) the presence of the dancing maenads, which is quite poorly represented in the dataset, in the list of highest values.

The combined analysis of Betweenness Centrality, Mean Weighted Degree and Modularity consents to define the local importance of each one

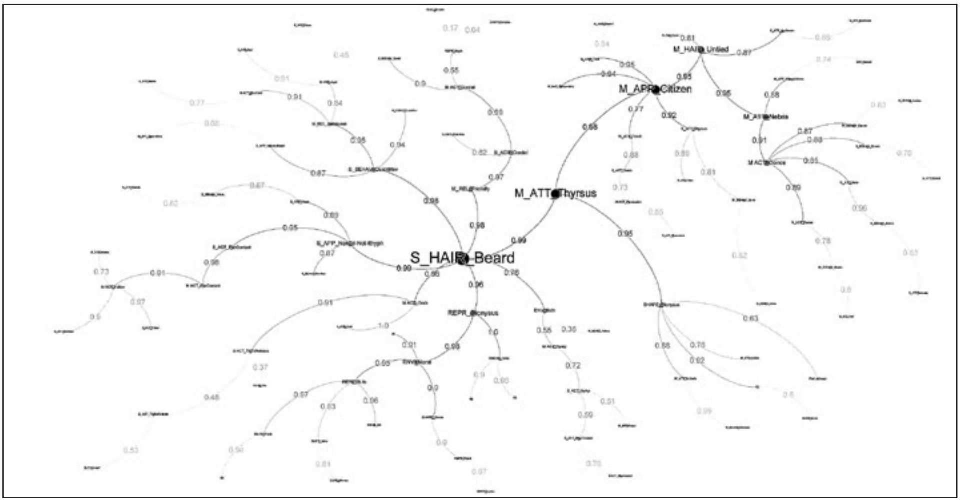

Fig. 1 – Betweenness Centrality.

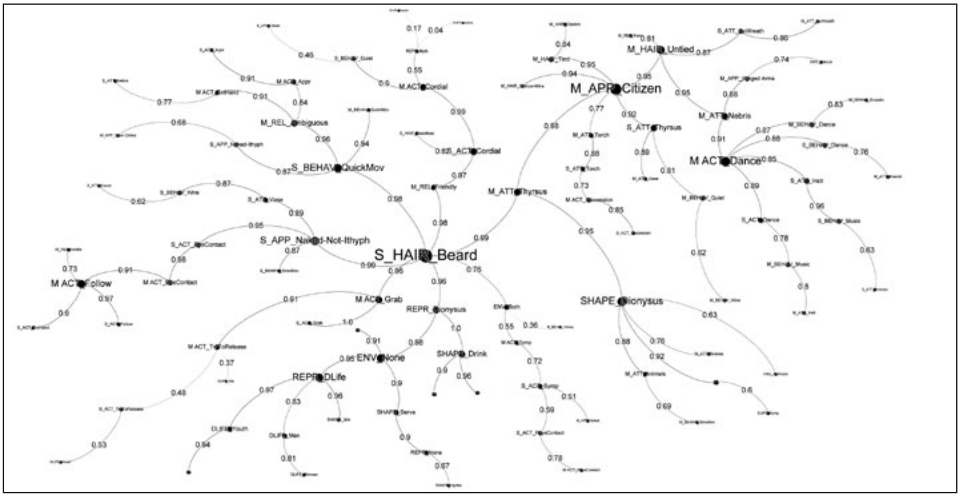

Fig. 2 – Mean Weighted Degree of Nodes.

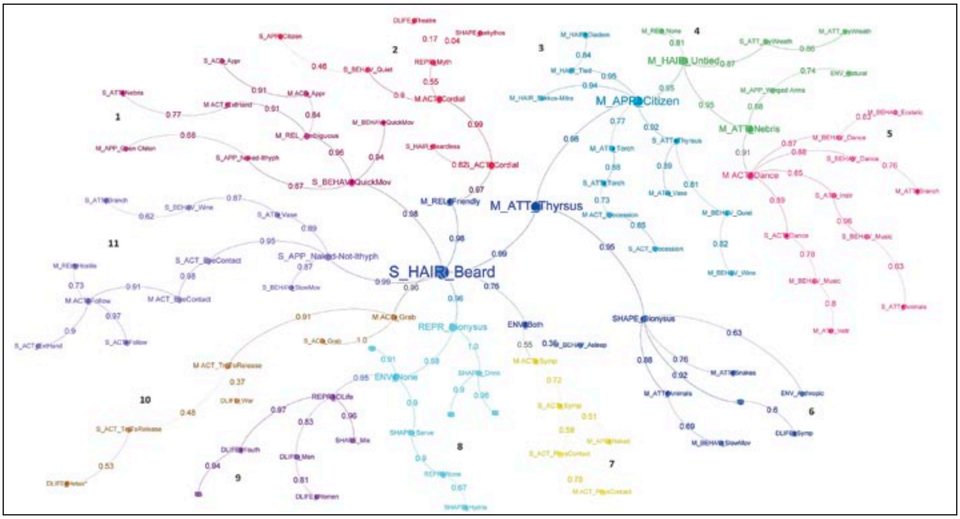

Fig. 3 – Modularity 1.

of those variables within the sub-structures (clusters) created by Modularity. Fig. 3 displays the first level of the Modularity analysis: with a resolution coefficient of 1, eleven clusters are defined. We can observe that the six

Variable	Label	BetC.
Satyrs : Beard	S_HAIR_Beard	0.78
Maenads : Thyrsus	M_ATT_Thyrsus	0.53
Maenads : **Citizen**	M_APP_Citizen	0.48
Maenads : Untied Hair	M_HAIR_Untied	0.30
Vases : Other Repr : Dionysiac	REPR_Dionysus	0.26
Maenads : Nebris	M_ATT_Nebris	0.24
Maenads : **Dance**	M_ACT_Dance	0.20
Vases : Environment : **None**	ENV_None	0.20
Satyrs: Naked not ithyphallic	S_APP_Naked-Not-Ithyph	0.20
Satyrs : **Quick** Movement	S_BEHAV_QuickMov	0.16

a

Variable	Label	WDeg.
Satyrs : Beard	S_HAIR_Beard	6.62
Maenads : **Citizen**	M_APP_Citizen	5.50
Maenads : **Dance**	M_ACT_Dance	4.40
Vases : Other Figure : Dionysus	SHAPE_Dionysus	4.13
Satyrs : **Quick** Movement	S_BEHAV_QuickMov	3.75
Vases : Environment : **None**	ENV_None	3.74
Vases : Other Repr : **Daily Life**	REPR_DLife	3.70
Satyrs: Naked not ithyphallic	S_APP_Naked-Not-Ithyph	3.70
Maenads : Untied Hair	M_HAIR_Untied	3.58
Maenads : Following/Followed	M_ACT_Follow	3.51

b

Tab. 2 – The ten highest values of: a) Betweenness Centrality (BetC.) and b) Weighted Degree (WDeg.)..

Cluster Nb.	Central Node	Variable	WDeg.
1	S_BEHAV_QuickMov	Satyrs : **Quick** Movement	3.75
2	S_ACT_Cordial	Satyrs : **Cordial**	2.78
3	M_APP_Citizen	Maenads : **Citizen**	5.50
4	M_HAIR_Untied	Maenads : Untied Hair	3.58
5	M_ACT_Dance	Maenads : **Dance**	4.40
6	S_HAIR_Beard	Satyrs : Beard	6.62
7	S_ACT_Symp	Satyrs : **Symposium**	1.81
8	ENV_None	Vases : Environment : **None**	3.74
9	REPR_DLife	Vases : Other Repr : **Daily Life**	3.71
10	M_ACT_Grab	Maenads : Grabbing/Grabbed	2.87
11	S_APP_Naked-Not-Ithyph	Satyrs: Naked not ithyphallic	3.70

Tab. 3 – Modularity 1: Clusters, Central Node, Corresponding Variable and Weighted Degree value (WDeg.).

figures variables with the highest values of both Betweenness Centrality and Mean Weighted Degree constitute the central nodes of different clusters, as highlighted in Tab. 3.

4.2 *The bearded satyrs and other variables*

Cluster 1, which is focused on the satyrs' quick movement behaviour, is composed of nine variables and remains stable until Modularity 3. Tab. 4 presents the nodes in Cluster 1, classified by their value of Mean Weighted

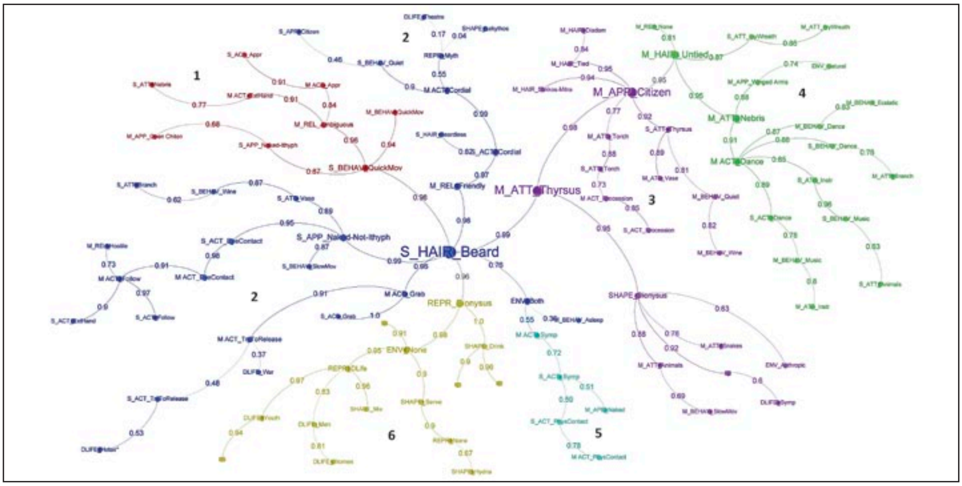

Fig. 4 – Modularity 3.

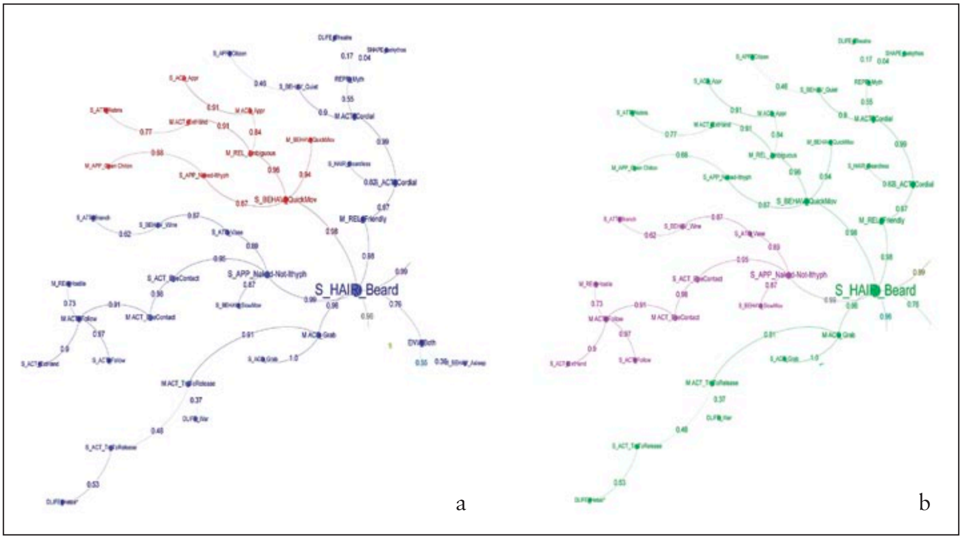

Fig. 5 – Modularity 3 (a) and 4 (b): the evolution of the satyrs' clusters.

Variables	Nodes	WDeg.
Satyrs: Quick Movement	S_BEHAV_QuickMov	3.75
Maenads: Ambiguous	M_REL_Ambiguous	2.71
Maenads: Approaching/Approached	M_ACT_Appr	1.75
Maenads: Extended Hand	M_ACT_ExtHand	1.68
Satyrs: Naked Ithyphallic	S_APP_Naked-Ithyph	1.55
Maenads: Quick Movement	M_BEHAV_QuickMov	0.94
Satyrs: Approaching/Approached	S_ACT_Appr	0.91
Satyrs: Nebris	S_ATT_Nebris	0.77
Maenads: Open Chiton	M_APP_Open Chiton	0.68

Tab. 4 – Cluster 1, Modularity 1-3: Nodes and Mean Weighted Degree.

Degree. With Modularity 4, this group of variables is absorbed by the big cluster focused on the satyrs' beard (see *infra*, Fig. 5). As presented in Tab. 4, Cluster 1 does also include various maenads' variables, first of all the ambiguous reaction to the satyrs' approaches: we can therefore consider that the quick movement and ithyphallic iconographic elements are strongly correlated to the type of reaction enacted by maenads.

Cluster 6 is focused on the global central node, the satyrs' beard, but its inner structure appears to be poorly compact. Indeed, the nodes belonging to the bearded satyr's cluster change with each modification of the resolution coefficient. At Modularity 1 and 2 it contains the node of the *thyrsus* as a maenadic attribute, which is then absorbed in the cluster focused on the maenads' citizen appearance. Fig. 4 presents the Modularity graph obtained with a resolution coefficient of 3, and shows the evolution of the clusters into six bigger clusters. Cluster 11 of Modularity 1 (Fig. 3) is focused on the non ithyphallic appearance of the satyrs, and does not present a strong structure. As soon as Modularity 2 part of Cluster 11 is absorbed by Cluster 2; at Modularity 3 the whole Cluster is part of Cluster 2 (Fig. 4). The evolutions of Clusters 1 and 11 of Modularity 1 and their alternating inclusion in the bigger Cluster 2, which is focused on the bearded satyrs, between Modularity 3 and 4 is presented in Fig. 5. It is interesting to note that at Modularity 4 the inclusion of Cluster 1, which is focused on the quick movement and includes the ithyphallic satyrs, implies the exclusion of the group based on the non-ithyphallic appearance of the satyrs, which now forms Cluster 1. Therefore, the ithyphallic and non-ithyphallic appearances are maintained in different clusters (respectively 1 and 11 of Modularity 1; 1 and 2 of Modularity 3; 2 and 1 of Modularity 4) until Modularity 5.

Another interesting result is the association, in Cluster 11, of non-ithyphallism and other dignifying elements of the iconography of satyrs with the clearly hostile reaction of the maenads. This association splits with Modularity

2, when the sub-group focused on the hostile maenads are forming a small, independent cluster, but reunite at Modularity 3, as shown in Fig. 4. As presented in Tab. 3 and Fig. 3, the small Cluster 2 is focused on the satyrs' cordial action and it includes three peripheral vases variables and four variables related to figures' appearance and behaviour: the maenads' cordial actions, the citizen and the beardless satyrs, and the quiet behaviour of the satyrs. It is interesting to note that, while in the general structure of the graph the same behaviour and actions related to the two figures are often directly correlated, in this case the quiet behaviour of the maenads is classified in another cluster (Cluster 3) until Modularity 6. Cluster 2 is absorbed by Cluster 6 since Modularity 2.

4.3 *The citizen maenads and other variables*

As seen in Fig. 3, the central node of Cluster 3 is the citizen appearance of the maenads. The Cluster maintains its inner structure for only two levels of Modularity (1 and 2), then it includes the sub-group focused on the *thyrsus* and remains stable until Modularity 5. The *thyrsus* as a maenadic attribute (M_ATT_Thyrsus: 165 items, 69% of all maenads) presents, as expected and in conformity with its high frequency, the second highest value of Betweenness Centrality but, unexpectedly, it is not even present among the highest Mean Weighted Degree values. Another unexpected element is represented by the evolution of the *thyrsus*' inclusion in different clusters: at Modularity 1 and 2, the *thyrsus* is part of the Cluster focused on the bearded satyrs (Fig. 3); from Modularity 3 to 5 (Fig. 4) it is included, more logically, in Cluster 3, which comprises many maenadic elements; at Modularity 6, with the final visualisation of three big clusters, the *thyrsus* returns, surprisingly, to be correlated with the bearded satyr (Fig. 6). The general evolution of Cluster 3 at Modularity 3 is exposed in Fig. 4. Two sub-clusters that steadily remain in Cluster 3 might inform us on the cultual relationships of satyrs and maenads: the first is composed of torch and procession, the second is focused on the *thyrsus* as a satiric attribute. Tab. 5 displays the nodes contained in Cluster 3, classified by their Weighted Degree values, for Modularity 1-2 (a) and 3-5 (b).

Clusters 4 and 5 of Modularity 1 are respectively focused on the untied hair and on the dance action of the maenads. They both include various alterity variables, such as the attribute of the animal skin (*nebris*) and the ecstatic behaviour. Cluster 4, which is focused on the untied hair, is also correlated to the absence of reaction of the maenads to the satyrs' approaches. Since Modularity 2 the two small clusters merge and form bigger Cluster 4 (Fig. 4), maintaining the same structure up to Modularity 5. Tab. 6 presents the nodes contained in Clusters 4 and 5.

The composition and evolution of Clusters 3, 4 and 5 are very interesting. As already seen, they are all focused on a different and important maenadic component, respectively citizen appearance, untied hair, and dance. We

Variables	Nodes	WDeg.
Maenads : Citizen	M_APP_Citizen	0.48
Satyrs : Thyrsus	S_ATT_Thyrsus	0.06
Maenads : Torch	M_ATT_Torch	0.06
Satyrs : Torch	S_ATT_Torch	0.04
Maenads : Tied Hair	M_HAIR_Tied	0.02
Maenads : Quiet	M_BEHAV_Quiet	0.02
Maenads : Procession	M ACT_Procession	0.02
Maenads : Sakkos-Mitra	M_HAIR_Sakkos-Mitra	0.00
Maenads : Diadem	M_HAIR_Diadem	0.00
Maenads : Vase	M_ATT_Vase	0.00
Maenads : Wine Service	M_BEHAV_Wine	0.00
Satyrs : Procession	S_ACT_Procession	0.00

a

Variables	Nodes	WDeg.
Maenads : Thyrsus	M_ATT_Thyrsus	0.53
Maenads : Citizen	M_APP_Citizen	0.48
Vases : Other Figure : Dionysus	SHAPE_Dionysus	0.12
Satyrs : Thyrsus	S_ATT_Thyrsus	0.06
Maenads : Torch	M_ATT_Torch	0.06
Satyrs : Torch	S_ATT_Torch	0.04
Maenads : Animals	M_ATT_Animals	0.02
Period 1	P1	0.02
Maenads : Tied Hair	M_HAIR_Tied	0.02
Maenads : Quiet	M_BEHAV_Quiet	0.02
Maenads : Procession	M ACT_Procession	0.02
Vases : Environment : Anthropic	ENV_Anthropic	0.00
Vases : Other Repr : Daily Life (Symp.)	DLIFE_Symp	0.00
Maenads : Snakes	M_ATT_Snakes	0.00
Maenads : Slow Movement	M_BEHAV_SlowMov	0.00
Maenads : Sakkos-Mitra	M_HAIR_Sakkos-Mitra	0.00
Maenads : Diadem	M_HAIR_Diadem	0.00
Maenads : Vase	M_ATT_Vase	0.00
Maenads : Wine Service	M_BEHAV_Wine	0.00
Satyrs : Procession	S_ACT_Procession	0.00

b

Tab. 5 – Cluster 3, Modularity 1-2 (a) and 3-5 (b): Nodes and Mean Weighted Degree.

can observe that two different and strong groups of maenadic elements, the first (Cluster 3) focused on the matron appearance and the second (Clusters 4 and 5, then 4) on wilder components, maintain an inner cohesion and remain separate until Modularity 5. Finally, at Modularity 6, they merge and form a huge maenad-determined cluster (Fig. 6, Cluster 3). As seen in Figs. 3 and 4, the small Cluster 7 (then 5) of Modularity 1 remains an independent small cluster composed of infrequent variables until Modularity 3. It includes only five vari-

Variables	Nodes	WDeg.
Maenads : Untied Hair	M_HAIR_Untied	0.31
Maenads : Nebris	M_ATT_Nebris	0.24
Maenads : Dance	M ACT_Dance	0.20
Satyrs : Instrument	S_ATT_Instr	0.04
Satyrs : Dance	S_ACT_Dance	0.04
Maenads : Winged Arms	M_APP_Winged Arms	0.02
Satyrs : Ivy Wreath	S_ATT_IvyWreath	0.02
Satyrs : Music	S_BEHAV_Music	0.02
Satyrs : Dance	S_BEHAV_Dance	0.02
Maenads : Music	M_BEHAV_Music	0.02
Maenads : Dance	M_BEHAV_Dance	0.02
Vases : Environment : Natural	ENV_Natural	0.00
Maenads : Ivy Wreath	M_ATT_IvyWreath	0.00
Maenads : Relationship : None	M_REL_None	0.00
Satyrs : Animals	S_ATT_Animals	0.00
Maenads : Branch	M_ATT_Branch	0.00
Maenads : Instrument	M_ATT_Instr	0.00
Maenads : Ecstatic	M_BEHAV_Ecstatic	0.00

Tab. 6 – Evolution of Clusters 4 and 5 of Modularity 1 (then Cluster 4, Modularity 2-5): Variables, Nodes and Mean Weighted Degree (WDeg.).

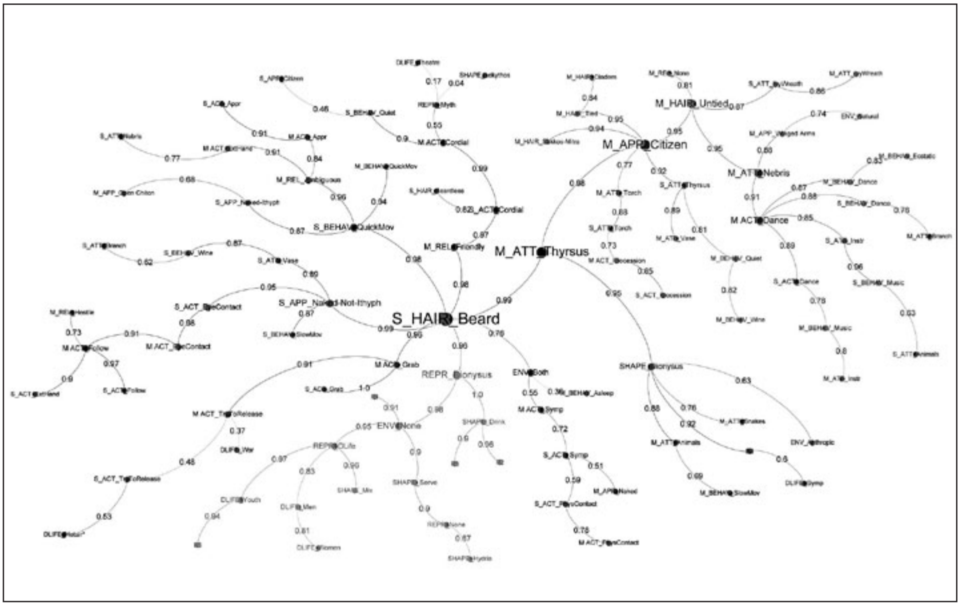

Fig. 6 – Modularity 6.

ables, all connected through low weighted values and somehow related to the symposiac iconography. Finally, Fig. 6 shows the final division into three clusters at Modularity 6: we can observe that the central variables relating to each figure are maintained in separate clusters. Cluster 1 includes the three central satyrs variables, beard, quick movement and not ithyphallic. Cluster 3 encompasses the three central maenads' variables, the untied hair, the citizen's appearance and the dance. The smaller Cluster 2 is only composed of vases variables, highlighting an interesting result that should be discussed in a further part of the research.

5. Bearded satyrs and citizen maenads: the data interpretation

5.1 *The beard*

As expected having regards to its diffusion, the beard of the satyrs is the central element of the graphs. On the one hand, such result expresses the coherence of the applied methodology, in terms of adherence between the results and the distribution frequency of the variables within the dataset, since the graph has recognised as central a characterising element of the iconography of satyrs. The adult satyrs are always represented bearded, and this element characterises them as male characters. Indeed, on Athenian vase-painting, the beard is an iconographic element of the male, adult citizen, and the beardless face, as for the iconography of satyrs, is generally reserved to young men, as presented in some homoerotic scenes of seduction. On the other hand, the visualisation graphs here presented also go deeper in the exploration of the qualitative and quantitative centrality of the satyrs' beard, by presenting its connections with other elements, in particular the *thyrsus* that would represent its maenads' counterpart, in terms of specificity and sensibility, and the central elements of the two clusters comprising satyrs' appearances and maenads' reactions.

5.2 *Sexuality and reaction*

As already stated in our previous paper, and in contrast with the traditional interpretation of the satyrs, in our sample the satyrs are mostly represented naked but not ithyphallic. The importance of the non-ithyphallic appearance of the satyrs is now confirmed by the ANN-based analysis, which highlights its centrality for the global structure of the graph and its importance as the central node of one quite compact cluster. The non-ithyphallic appearance expresses a deliberate humanisation of the satyrs on red-figure vases. This humanisation of the satyrs depicted as maenads' companions on symposium vases might have enhanced a certain degree of identification between the figures and the vases' beholders, in this case the Athenian citizens gathered for the symposium. Given that Athenian citizens' figures are rarely represented in Dionysian iconography, the representation of moderate satyrs may have

Fig. 7 – Cup by the Kleophon Painter, 430-420 BC, Oxford 1925.621 (ARV2 1147,68).

offered the citizens a possibility to identify themselves with the figures, which might thus be interpreted as "symmetrical doubles" of the citizens.

The results have also demonstrated that the two different appearances of the satyrs defined by sexuality, ithyphallism and non-ithyphallism, are never united in the formation of iconographic types. They represent two different ideal types of the iconographic creation of satyrs: on one side the sexually innocuous, somehow humanised satyr, on the other the hybrid man-beast being defined by his chaotic gestures and wild sexuality. The first iconographic type, which is focused on the satyrs' non-ithyphallic appearance, presents an intriguing correlation with the clearly hostile reaction of the maenads to the satyrs' approaches. Such association might mean that the maenads' clear violence does not generally derive from an evident visual threaten of the satyrs. Indeed, the action variables expressing a physical contact between the figures are not correlated to the maenads' violence. According to this interpretation, the maenads would react with violence only to the non-explicit approaches of the satyrs, maybe expressing, through the dichotomy between humanised satyr and violent woman-maenad, the otherness of maenads rather than that of satyrs. Fig. 7 shows the external scenes on a cup by the Kleophon Painter:

four maenads are reacting with a clear hostility to the approaches of four non-ithyphallic satyrs, threatening them with their attributes (*thyrsus*, torch and rock) used as weapons.

The maenads are here all well-dressed with a long, decorated *chiton*, and tied hair. In this case study, the altered figures, in the male imaginary, might have been the women becoming hunters rather than the satyrs, transmitting two different visual messages to the vases' beholders: on one side, the otherness of satyrs is tacit, since it represents a very common literary and iconographic stereotype to the Athenian community; on the other side, the satyrs do also represent a masculine principle as opposed to the women and their supposed wild nature, which constitutes another popular stereotype, even more, we can imagine, in a male-dominated assembly like the *symposium*. The image on the tondo of the same cup seems to emphasise such reading: a non-ithyphallic satyr is playing pipes next to Dionysus: the proximity and intimacy between the God and his attendant highlight the men-God intermediary function held by satyrs.

Indeed, the satyrs are hybrid beings standing at the intersection between man and beast but also between man and God. In this perspective, the man coming closer to Dionysus through the ritual wine consumption would go through a symbolic satiric transformation, and the non-ithyphallic satyrs of the externals might recall the one on the tondo, enhancing the man-satyr identification by means of the contact with the God. In other words, the tondo would allow a first level of identification between the drinker and the satyr, through the emptying of the wine contained in the cup, the satyr becoming the symmetrical double of the male citizen. The external figures would then emphasise such identification through the genre contrast: in the presence of two wild figures, the male principle will always appear more understandable to the male imaginary than the female one.

The non-ithyphallic satyrs are also correlated, as expected, to some dignifying elements, especially one sub-cluster involving cult components (the satyrs' wine service and the attributes of vases and branches) which might express a transformation of men into satyrs for the worship of Dionysus, as argued by some scholars (Frontisi-Ducroux 1986; Bérard, Bron 1986; Bérard 1992). The interpretation of satyrs as male worshippers is a complicated question that would require a specific iconological analysis. Indeed, if the lack of male citizens in the Dionysian imagery might incite the reading of satyrs as men, at the same time in the Athenian classical society the satyrs fulfil a number of meanings that sometimes seem to contradict such idea, in the overall context of a civilised and integrated Dionysism.

The second category in the iconography of satyrs is focused on the attitude of quick movement and it includes the ithyphallic appearance and the maenads' ambiguous reaction to the satyrs' approach. The turbulent gestures of the satyrs, run or dance, would need further characterisation in order to better define their possible meanings. Nonetheless, certain components are already recognisable. On the one hand, the association between ithyphallism and non-human, or at least non-citizen gestures might express the satyrs' bestiality, in continuity with the archaic type of black-figure silens, and therefore enhance their intermediate man-beast status.

The *nebris* as a satiric attribute would, in this perspective, emphasise the visual characterisation of satyrs as hybrid beings, in a century where the humanisation of satyrs seems to have been the rule. On the other hand, the gestuality of the satyrs might have expressed the *thiasos* component of the scenes. The association of ithyphallism and quick movement with maenads' variables quick movement and open *chiton* might strengthen this interpretation. Indeed, the quite rare open *chiton* might have represented an element of continuity with the archaic type of the uncharacterised nymph in the Dionysian cortege. At this stage of the analysis we can identify two different iconographic groups based on the sexual appearance of the satyrs: the first group expresses a typically classical iconography, which appears with the red-figure technique and is characterised by progressively dignified satyrs; the second group, on the contrary, follows the tradition of the black-figure representations of the Dionysian *thiasos*, defined by ithyphallic satyrs and by a confusion in the identity of the female followers.

As confirmed by the graphs, the ithyphallic appearance of the satyrs is strongly correlated to the ambiguous reaction of the maenads. In most cases the scenes are suspended in an undefined moment of the satyr-maenad interaction. While the satyr's wild sexuality is clearly exposed in other satiric iconographies (Lissarrague 1987), with the maenads the intercourse is never represented. The association between satyrs' ithyphallism and maenads' ambiguity shows that, when the satyrs' erotic intention is clear, the maenads' possible reaction is never foregone.

This peculiar choice of the vase-painters was probably employed in order to let the beholder decide on the possible conclusion of the scene (intercourse or maenad's hostile reaction) according to their convictions and prejudices about maenadism in particular and women's behaviour in general. Both the possible conclusions of the scene are present in Euripides' tragedy *The Bacchae*, composed at the end of the century (405 BC circa), where Pentheus' diffidence about the conduct of Thebes' women transformed in maenads by the god (vv. 217-225) contrasts with their effective cast behaviour (vv. 686-688). Fig. 8 presents, on the tondo of a cup by Makron, the strong correlation between ithyphallism and ambiguity which is now confirmed by the Modularity analysis.

The ithyphallic satyr is grabbing the maenad's shoulders with one hand and introducing his other hand under her dress. While her arms and legs seem to suggest that she is trying to release herself, her chest is twisted towards

Fig. 8 – Cup by Makron, 490-480 BC, Paris G144 (ARV2 462,43).

Fig. 9 – Cup by the Euaion Painter, 440 BC circa, Frankfurt STV6 (ARV2 790,11).

him, she embraces him, an intense eye contact is established, and their faces almost touch each other. The ambiguity is here clearly expressed by both the contrasting movements of her body and her attributes. The leopard she is grabbing by the tail characterises her as a hunter, expressing the hidden otherness of women practicing a typical male activity, but might also insinuate some kind of polysemy between the female animal (characterised by the breasts of a nursing female) and the woman holding it, introducing an additional genre element to the scene. And the *thyrsus*, which is emphasised by its horizontal close-up position, might, in the hypothetical violent conclusion of the scene, become a weapon used by the maenad to attack the satyr. The maenad here depicted might either react with violence to the erotic approach of the satyr or succumb to his advances. The conclusion of the interaction is up to the beholder, the male citizen which is drinking the wine contained into this cup, revealing the image and all its possible meanings.

Some rare representations of citizen-dressed or beardless, young satyrs are always related to the cordial attitudes of both the figures. Citizen-satyrs are quite rare on both black and red-figure vases and they would require a specific iconological study in order to understand all the possible implications of such iconographic choice. In our sample they are always depicted in cordial scenes together with friendly maenads (Crater London E467; Crater Paris G422; Crater Warsaw 142355). The rare beardless satyrs are young or children who are depicted in some particular iconographies of a satyr family including an adult satyr, a maenad and a young, beardless satyr (Crater London E467; Stamnos London E447; Crater Karlsruhe 208; Crater Madrid 11075), as servants of matron-dressed maenads (Pelike Taranto 143547; Crater Paris

G422), or in other unique iconographies (Crater Compiègne 1025; Chous Berlin 3242; Pelike Oxford 284).

5.3 *The maenads*

In our sample, the maenads appear to be represented mostly as Athenian women, with the long Ionian *chiton* eventually covered, partially or completely, with a *himation*. The iconographic type of the matron-dressed maenad represents an element of disruption with the archaic type of the half-naked nymph, while the continuity with this fortunate female figure would have been represented by the rare open *chiton*, as described above. The citizen maenads also appear to be identified by different elements of matron-hairstyle, i.e. the tied hair sometimes adorned with a diadem, and the headband covering entirely or partially the hair, as clearly displayed by the connections between the variables. The variables identifying citizen maenads are strongly correlated to two interesting sub-clusters.

The first sub-group includes the "wine service" attended by maenads, a wine-pouring gesture that can be interpreted either as ritual or as a daily life wife-husband interaction, since it appears to reproduce the model of such common iconographies: on one side, the ritual wine libation, on the other the wife serving wine to her husband. In the first case, the rituality of the action would characterise the figures as human or mythical worshippers. In the second case, the transposition of a normal, human genre interaction to the world of maenads and satyrs might have emphasised their function of symmetrical doubles of the Athenian citizens. In any case, the maenadic wine service is a peripheral variable which is correlated to the *thyrsus* as a satiric attribute. The *thyrsus*-bearer satyrs are quite rare in our dataset (10% of all satyrs) and they might either introduce an element of visual confusion between male worshippers of Dionysus and satyrs, or even characterise the satyrs as worshippers. In both cases, the satyrs in such iconographies would be interpretable as an exploration of different aspects of male identity in all those contexts in which representing Athenian citizens would not have been considered appropriate (Lissarrague 1998, 2000).

The second sub-cluster which is connected to the citizen maenads comprises the procession and the torch attributed to both the figures. Such association confirms the nocturnal nature of Dionysian processions, as stated by sources and modern studies (Villanueva-Puig 1992), and might introduce a further element of humanisation of the figures to the general picture of the maenads and satyrs identities. Furthermore, the nocturnal processions involving maenads and satyrs and represented through the presence of torches might have strengthen the confusion introduced by the God of the mask in the human life: just as the wine, the moving lights of the nocturnal torches would blur the participants' identities, allowing an analogy on one side between the symposium and the representation, on the other side between the otherness of the figures participating in nocturnal processions and the one of the male citizens gathered for the wine ritual.

In any case, both the sub-clusters connected to the citizen maenads, the procession and the wine service, are inspired by human iconographies, either as worship representations or as parodic deformations of human genre relationships. Fig. 9 presents one of those ritual or daily life scenes of wine-pouring, on the tondo of a cup by the Euaion Painter: a naked, non-ithyphallic satyr, holding a *kantharos* and a small branch is facing a graceful maenad with a *thyrsus* who is holding an *oinochòe*. The eye contact between the two, the quietness of the whole scene and another *thyrsus* standing in the field behind the satyr communicate a perfect harmony between the figures. This calm, respectable representation of wine-pouring clearly appeared to the citizen while he was emptying his wine cup. Reaching an inebriated state, the symposiast's reading of the scene may have evolved to his own identification with the quiet satyr and, by association, to the interpretation of the female figure as a feminine component of his life, either as the *hetaera* in charge of the wine service at the symposium or as the wife serving her husband.

The presence of the maenads' untied hair as the central variable of one strong cluster constitutes one of the most interesting results of this research. Indeed, while the citizen maenads are defined mostly by their dresses, as displayed in the graphs, the untied hair and their coherent associations appear to have a bigger influence on one specific iconographic type of the maenads than the accurate feminine hairstyle. The centrality of the untied hair for the creation of an iconographic type is partly joining the traditional conclusions of many scholars, who consider the untied hair as a determinant trait of maenads (Delavaud-Roux 2011).

However, through the clear separation and aggregation of the variables in clusters, the Modularity analysis is now allowing to interpret the untied hair as the central element not of all maenads but only of one of the possible types of maenads. The untied hair might have two different meanings. The first possible meaning of the untied hair is the wild and ecstatic behaviour of the maenads, where the hair would untie under the force of the violent dance movements. In this case the untied hair would represent a means of visual expression for the movement. The second possible meaning of the untied hair is an indication of the social status of the maenad: indeed, we know that the untied hairs in classical Athens were generally reserved to unmarried girls (Delavaud-Roux 2011).

Though it is not possible, on the basis of the current dataset, to establish the marital status of the maenads, their untied hair might be interpreted, on the basis of their association with other elements of alterity within Cluster 4, as the visual expression of the non-compliance with the social norms imper-

Fig. 10 – Hydria by the Kleophrades Painter, 490-480 BC, Basel XXXX0.1721 (ARV2 189,73).

sonated, for the male community, by the maenads. Indeed, the other variables contained in this cluster appear to be very coherent with the visual idea of wildness. The animal skin (*nebris* or *pardalis*) characterises the maenads as hunters, i.e. as women practicing a typically masculine activity, emphasising their diversity with the social rules regulating the life of women in Athenian society (Lissarrague 1990). The winged arms represent an iconographic element used mostly between 480 and 425 BC, which could express visually either the cold, windy wild spaces where the maenads were evolving or the rapid dance movements of the figures (Edwards 1960).

The clearly dancing maenads are not very frequent on the vases here analysed. Though, according to different scholars (Villanueva-Puig 1988; Delavaud-Roux 1991), the dance is one of the characterising elements of maenadism. Such traditional interpretation is now partially confirmed by the Modularity analysis. Indeed, the dancing maenads represent the centre of a cluster comprising mostly, but not only, elements defining both dance and music. The dance should then be considered as a characterising element of one specific type of the maenads' iconography, while the other types defined by the Modularity analysis are focused respectively on the citizen appearance and untied hair. Since Modularity 2, the cluster focused on dance and music joins the "alterity cluster" focused on the untied hair.

The graph thus presents two possible iconographic types of maenads. The first type is the citizen maenad: her hair are tied and sometimes covered with a headband, she is represented while attending ritual or daily life activities.

She is the maenad presented in Fig. 9 facing the standing, dignified satyr. The second ideal iconographic type of the maenad is presented in Fig. 10: three maenads are dancing to the music of pipes played by a lying satyr. Their hair are untied, their hands are covered by the long sleeves of their *chiton*. The first maenad on the left is represented in trance, facing the vase's beholder through the frontality which is rarely used on Athenian vase-painting, and always to express an altered state of consciousness (Tefnin 2003). The two definitive ideal types in the representation of maenads on Athenian red-figure vase-painting, the citizen maenad and the altered one, which contains the dancing figures, appear to be maintained deliberately separated. They might have expressed two different male interpretations of the maenads' behaviour, oscillating from the accepted, calm maenads whose appearance and behaviour would have instilled dignity, to the wildest attitudes attributed by men to those women who released themselves from their rigid social control.

6. Conclusions

The results of the data processing have highlighted several interesting elements. First of all, the importance of the figures' appearance in the definition of the satyr-maenad iconography, which had already been pointed out by previous researches, is now confirmed and extended to their different associations with other iconographic elements. In particular, the maenads' reaction to the satyrs' approach have been demonstrated to be strongly correlated to the sexual-based appearance of the satyrs. On the one hand, the ambiguous reaction of the maenads, which would have deliberately left the beholders decide the possible conclusions of the scenes according to their individual and social convictions about women's behaviour, appears to be strongly correlated to the non-ithyphallic appearance of the satyrs.

Such correlation, which highlights the absence of clear erotic approach of the satyrs, seems to confirm the ambivalence of male-based interpretations of the feminine lascivious or cast attitudes highlighted in Euripides' *Bacchae*. On the other hand, the maenads are clearly hostile mostly when their companions are not represented in the unambiguous erotic appearance of ithyphallism. The association of hostile maenads with non-ithyphallic satyrs might have enhanced ambivalent interpretations: in such correlation, which figure would represent the wildness, the humanised satyr or the hunting maenad? Such representations might have enhanced some genre-identity confusion among the beholders. Secondly, the very coherent division of the maenads' appearance into two strong structures, the first focused on the citizen appearance and the second on the untied hair, consented to define two different iconographies of maenads on Athenian red-figure vases. The first iconography is based on Athenian-looking maenads, well-dressed and accurately coiffed.

The second one comprises most of the alterity variables, highlighting the importance of the untied hair for the characterisation of wild maenads. Finally, the peculiar position, within the graph structure, of some of the variables, in particular the *thyrsus* as a maenadic attribute, and the iconological analysis of some of the elements here presented, would require a specific development and will be the subject of further researches. In conclusion, the interesting preliminary results of the application of ANN-based methodologies to the formalised study of Athenian iconography are opening new perspectives to the research. A further exploration of such methodologies, associated to a better definition of the dataset and to an expansion of the analysed variables, will allow innovative and important interpretative solutions to the study of the complex maenads-satyrs interactions on Athenian red-figure vases.

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ABSTRACT

This study aims at exploring both the identity of the maenads and their multiple interactions with the satyrs on Athenian red-figure vases by presenting the preliminary results of an ANN-based analysis applied to a dataset of 114 vases representing 478 figures (maenads and satyrs). The encouraging results seem to confirm the highly significant role of ANN-based methodologies as innovative tools for the organisation, visualisation and analysis of complex data in History of Art and Archaeology. Further explorations of these methodologies, associated with higher levels of data formalisation, should open new perspectives for the research on Athenian iconography and iconology.