Archeologia e Calcolatori
28, 2017, 93-108

FORMALLY DEFINING THE TIME-SPACE-ARCHAEOLOGICAL CULTURE RELATION: PROBLEMS AND PROSPECTS

1. Introduction

Archaeology is the discipline that investigates past events, through analysis of material culture and their context of finding. Common investigations are chemical-physical properties of artefacts and their context, geometric shape and texture, measurements or observations, or use wear signs and residues on their surface. Taphonomic factors, tradition, dexterity of artisan, style, overall savoir-faire, etc. are considered when interpreting the results of such analyses. Based on the results from above, categories are built for comparative studies, in order to reconstruct past social, cultural and economic structures.

Crucial in this intellectual exercise is their positioning in distinct time and space units. Absolute dating, references to historical notes, and other dating methods are applied to set the time frame of such remains; their geographic location is usually defined by the extent of their consistent appearance over a given area. Despite the recognised importance of this triumvirate (time-space-form) there are few attempts to formally describe this relationship; the challenge becomes particularly acute in modern times, when large digital infrastructure datasets become common, and more data is interconnected and available for further re-use. The article proposes a fuzzy logic based approach to formally represent the time-space-archaeological culture relation and discusses its possible implications to the archaeological research. Fuzzy logic and its related fuzzy sets theory have been successfully applied in the past to various aspects of archaeological research, such as typological classification (Hermon, Niccolucci 2002, 2003; Hermon *et al*. 2004), definition of temporal boundaries of survey data (Farinetti *et al*. 2010), and 3D visualisation aspects of virtual reconstructions (Hermon *et al*. 2006; Niccolucci, Hermon 2010; Hermon 2012).

2. A brief history of research

The relation time-space has been a topic of research since a long time and across many disciplines (Smart 1964), social sciences and archaeology being among (e.g. Willey, Phillips 1958; Lucas 1973; Foucault 1974; Shackle 1978; Fabian 1983; Thrift 1983; Baert 1992; Fletcher 1992; Murray 1999; Lucas 2005; see also Dodgshon 1999 for a discussion on time-space compression). Understanding how space and time influences the

nature of material culture (Spaulding 1960; Chang 1967; Cochrane 2002) is essential to any classification-based archaeological research (Rouse 1960; Sokal 1966; Dunnell 1986; Adams, Adams 1991; O'Brien, Lyman 2003), while the vagueness and uncertainty of such process has been described elsewhere (Hermon, Niccolucci 2003; Hermon *et al.* 2004).

Types and classes were regarded as archaeological measurement units (Dunnell 1971; Ramenofsky, Steffen 1998) upon which taxonomic units (Foley 1987) can be built and cultural developments explained (Willey, Phillips 1958; Boyd, Richerson 1985; Gamble *et al.* 2005). Archaeological cultures were described as an arbitrary segment in time-space (Willey, Phillips 1958) defined by «…reference to its imperishable content and whatever "common social tradition" can be inferred therefrom…» (Phillips, Willey 1953, 617). Understanding and quantifying the contribution of each of its three main components-form, time and space is therefore fundamental (Phillips, Willey 1953).

During the 60's and 70's of the last century, seriation (Kendall 1969, 1971) and its associated statistical methods (e.g. Marquardt 1978; Brainerd 1997; Ihm 2005) were proposed as a framework to discuss time-space-form relationship O'Brien and Lyman (2002) described how artefact-types are constructed by archaeologists as time measurement units, while their variation may fine-tune this process. Consequently, based on sets of attributes, they identify historical index types, or horizon-styles, which cover large geographic areas over brief time periods, versus historic types, or temporal types, appearing over a long time period but of little geographic distribution.

Papers in the 70's-90's of the last century discuss time and temporality in archaeology and their impact on the archaeological research (Leone 1978; Trigger 1978; Shanks, Tilley 1987a, 1987b; Knapp 1992; Stahl 1993; Clark 1994; Gosden 1994; Thomas 1996; Ramenofsky 1998; Karlsson 2001; Olivier 2001; Bailey 2007; Holdaway, Wandsnider 2008). The concepts of space, spatiality and scale became central (Rossignol, Wandsnider 1992; Peuquet 1994; Van der Leeuw, McGlade 1997; Lock, Molyneaux 2003), in particular in research performed within Geographic Information Systems and data visualisation (Allen *et al.* 1990; Lock, Stančič 1995; Wheatley, Gillings 2002; Andrienko *et al.* 2003). Statistical (probabilistic) methods (Andrienko, Andrienko 2005) were proposed to quantify the uncertainty of temporal positioning of archaeological events (Castleford 1992; Wandsnider 1992; Harris, Lock 1996; Daly, Lock 1999; Johnson 2004; Crema *et al.* 2010; but see Farinetti *et al.* 2010).

Recently, the space-time cube concept (Hägerstand 1970) was proposed to explain archaeological material culture-time-space relations (Kraak 2003; Kraak, Koussoulakou 2004; Husiman *et al.* 2009; Kveladze *et al.* 2013). Bach *et al.* (2014) proposed a temporal visualisation method based on

operations within a conceptual time-space cube. Space-time objects can be volumes, surfaces, curves, points or sets of disconnected volumes, representing the distribution of a culture, existence of a monument, development of a cultural process, etc. Such operations require a database with time-space intervals clearly defined, a well-expressed time-space relation and a known inner structure of the time-space cube, clearly a rare situation in archaeology. We must seek therefore a different approach, which considers the real nature of the relation time-space and its fuzzy boundaries (Niccolucci 2000; Farinetti *et al.* 2010).

As summarised above, despite the recognised importance of space-time in archaeology, and despite various methods proposed to deal with this concept, there are few articles that focus on their formal definition, characteristics, definition of boundaries, intrinsic relationship and how such relationships influence the way we analyse the past material culture.

3. Time-space and archaeological cultures

Why "time" matters? When "time" matters? How do we define "space"? While answering these questions is beyond the scope of this article, they are nevertheless at the heart of any attempt to reconstruct past events (Niccolucci, Hermon 2015a); suffice is to say here that their related identity criteria are located within (more or less) clear geographic and temporal boundaries and that the sharper such localisation, the clearer the reconstruction of its encapsulated event. We are also avoiding to enter into any detailed philosophical or theoretical discussion about the meaning, use or abuse of the term "archaeological culture", clearly summarized elsewhere (Roberts, Vander Linden 2011). For the sake of our argumentation in the article and in order to maintain a simple yet clear discussion, we refer to archaeological culture as a "set of archaeological events". We describe the process of its definition as follows:

1. Define an archaeological culture as a set of archaeological events, identified through observations on material culture. Its identity criteria are determined by the uniqueness of the archaeological events' characteristics and their inter-relationships, indicative of its internal structure.
2. Define temporal borders of the archaeological culture by dating its composing archaeological events. Their granularity and sharpness depend on the number, quality and level of overlapping of dated archaeological events.
3. Delineate the geographic distribution of the archaeological culture, according to the localities of its composing archaeological events. The same criteria as for temporal borders are applied here as well.
4. Assure the continuity of its time-space borders.

Three basic approaches are implemented for situating an archaeological event within a time frame: absolute (radiometric) dating, relative dating (based

on the universal principle of geologic stratigraphy), and the *terminus ante/post quem* approach (often related to a datable historic event). Commonly, a proposed time confine has an interval of possible existence, i.e. a calendar date with statistical margins of error. The spatial setting of an archaeological culture follows the same approach as for its time setting, namely uniqueness of space and linearity of its borders.

4. Example: the Cypro-Archaic

The example below highlights challenges when trying to integrate (vaguely defined) archaeological concepts into crisp digital structures or large-scale research infrastructures for data sharing and scientific reasoning. The (arbitrarily) chosen example is the Cypro-Archaic (period/culture), first mentioned and its material culture described in the report of the Swedish excavations in Cyprus (Gjerstad 1948), and since then frequently used (Reyes 1994; Knapp 1997). A recently published chronological table situates it at 750 B.C. to 480 B.C. with an internal sub-division at ca. 600 B.C. (Iacovou 2012), corresponding to shifts in political powers in the island (Gjerstad 1948). Apparently, the chronological frame and the internal sub-division of the Cypro-Archaic (as a pan-Cypriot phenomenon) were set according to historic events (most occurring outside the island, but with repercussions on it), which triggered changes in the socio-political organisation in Cyprus (Iacovou 2008). Researchers looked for changes in the material culture, describing stylistic gradual shifts in the pottery, statues or architecture (Karageorghis 1982, 1991). Accordingly, the Cypro-Archaic identity criteria are basically historical, with no clearly defined changes in the material culture, but rather variations in style.

It seems that the typical archaeological reasoning related to the definition of "archaeological cultures", as described above, was not followed for the Cypro-Archaic. Therefore, when trying to formalise and integrate its description in a large scale digital knowledge repository, the backbone of any global research infrastructure (Niccolucci, Richards 2013), we may not refer to it as an "archaeological event", but something else, either a historical event, or a hybrid that has yet to be defined within the existing domain ontologies, e.g. CIDOC-CRM (Doerr 2003; Sugimoto *et al.* 2007; Eide *et al.* 2008). How then should we address the Cypro-Archaic and how to formally describe its space-time-form relation?

5. Formally addressing the time-space-archaeological culture relation

CIDOC-CRM is an ontology addressing archaeological matters (Niccolucci *et al.* 2015), instrumental in developing information systems and

providing the framework for conceptual modelling. It has yet to solve how to express and represent vague or poorly defined concepts, common in archaeology, such as the timespan of the Cypro-Archaic. Its starting date, 750 B.C. is set by a stela found in 1844 in the *debris* of a medieval ruin at Bamboula (part of the larger archaeological site of Kition), exhibited at the Berlin State Museum (Radner 2010). It relates to the Assyrian king Sargon II, who reigned between 722-705 B.C. Its internal sub-division and end are set by political events (recorded in written texts, inscriptions or coins in Cyprus and neighbouring countries), such as a short political independency of Cypriot kingdoms, followed by their subjugation to Egyptian and later on Persian rulers.

Should the spatial borders of the Cypro-Archaic be drawn around the "seven kingdoms of Ya", a district in Adnana (the Assyrian name for the island), as it appears on the mentioned above stela? In later Assyrian inscriptions (Radner 2010) ten kingdoms and their kings are mentioned by their respective names; apparently, their combined geographic distribution covers most of the island's territory (Iacovou 2008). Thus, its spatial borders can be drawn around: (a) the administrative district of Ya; (b) the ten kingdoms of the island (not all fully identified); (c) Cyprus in its entirety.

6. A mathematical-logical approach for expressing archaeological cultures

Archaeological cultures are defined according to material remains. These are sets of artefacts, grouped according to commonly agreed criteria, such as matter (clay, flint, stone, bone, ivory, glass or wood), form (statues, vessels, figurines), etc. Each defined set must comprise unique characteristics that distinguish them from other sets in a given time/space segment. Thus, such uniqueness must exist along the three axes: time, space and archaeological matter. Previously, we proposed to represent chronology and dating in a simple mathematical way, which is the translation of the statement «an archaeological culture existed within geographical borders and dated to a unique time interval» (Niccolucci, Hermon 2015b). Consequently, an archaeological culture is (ideally) represented by a (finite) set of events, which define and characterize it (Fig. 1). The reality may be slightly different (Fig. 2), since events may continue into another archaeological culture, start earlier or may exist contemporaneously in more than one. Examples of events are pottery production, architectural construction style, a bone industry, etc. Each event is composed by features, which determine their uniqueness and separate them from similar others in other archaeological cultures. Examples of features are technological choices implemented in the production of cooking wares, geometry of such artefacts or their decoration. These may be defined categorically, through quantitative analysis, qualitatively, by presence/absence

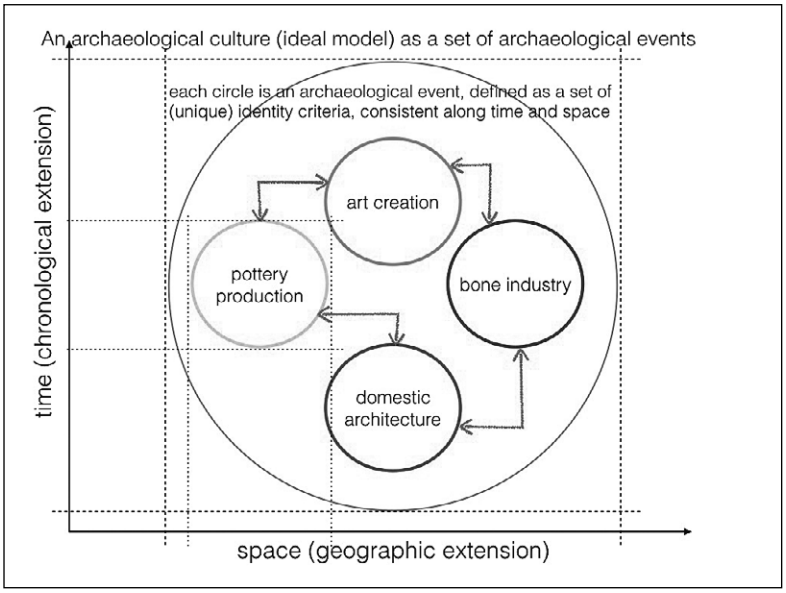

Fig. 1 – Archaeological cultures represented as sets of archaeological events in a given time-space (idealised).

of particular aspects, or through subjective statements of belief (e.g. features present archaic forms).

In mathematical terms, we describe AC (archaeological culture) as a set of events e_n where n is the number of events that define AC. The chronological relation between events is a pre-order relation on the set AC of the events considered in the discourse, i.e. a binary relation $\leq_C$ which is reflexive and transitive. If *AC* is the set of all events, a chronology is a relation such that for any events *e,* $e1$, $e2$ and $e3$ the following holds:

$$e \leq_C e$$

if $e1 \leq_C e2$ and $e2 \leq_C e3$ then $e1 \leq_C e3$.

The duration of an event is the mapping *f* from AC to , which assigns a real number to an event. The duration measures the time-span of the event. If there is a dating, the duration of an event can be computed as follows:

$$f(e) = \sup(d(e)) - \inf(d(e))$$

where *d* is the (absolute) dating of the event. For example, if some type of pottery characterizes the event *e* and there are several samples of such a

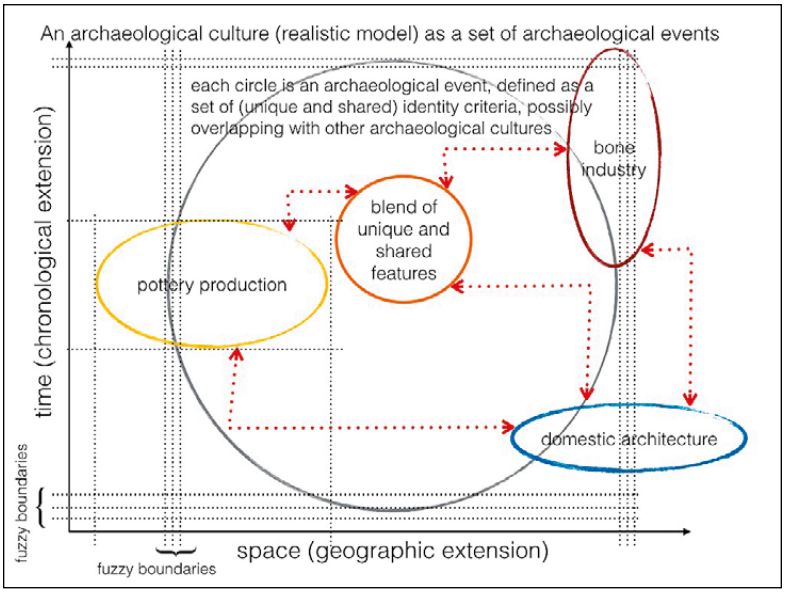

Fig. 2 – Archaeological cultures represented as sets of archaeological events in a given time-space (realistic).

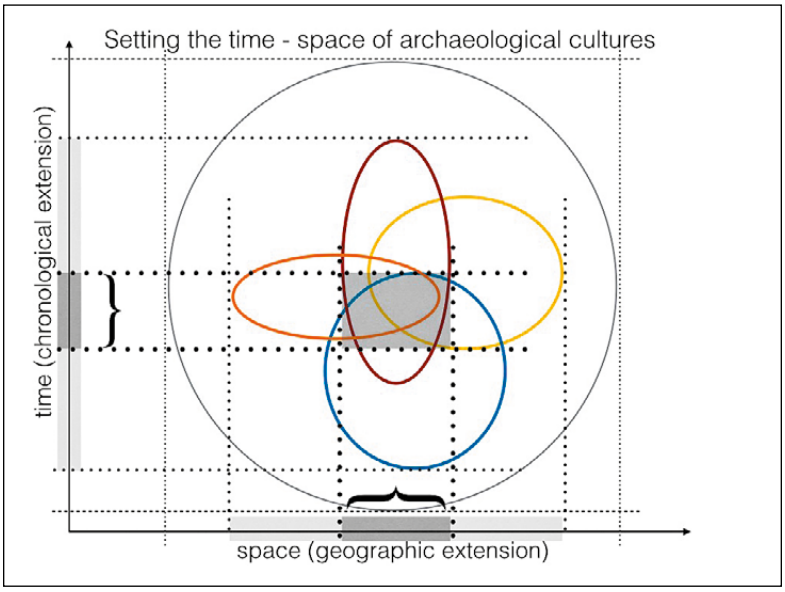

Fig. 3 – Representation of time-space of archaeological cultures.

pottery with respective dating, the duration of the event "use of that kind of pottery" is the difference between the latest appearance of the pottery and its earliest appearance.

The overall time interval of AC is determined by the granularity of dating, the duration and the overlapping degree of its defining events (Fig. 3). An immediate and intuitive result of such a depiction is that we may define several time intervals for AC, according to the degree of allowed overlap between time spans of *e*: a restricted one as the intersection of all events *e* composing AC (marked with the rectangle in Fig. 3), or at any combination of *e* time-spans archaeologists wish to choose, corresponding to various considerations. Such a representation may also be used as an indicator for the quality of positioning AC within a timeframe, based on its defining events' time-spans. The same reasoning is applicable along the "x" axis in Fig. 3, related to the geographic extent of the archaeological culture.

Neither relative nor absolute dating can provide an exact chronology for archaeological events, due to the granularity of time or space (the measuring units) and the imprecision of assigning a beginning/end or a clear geographic demarcation for such events. Statements such as "The Villanovan culture of Northern Italy started at 1100 BC, 1st of January, and ended at 31st of December 700 BC" is of course ridiculous, but exemplifies the above. Moreover, mentioning that it preceded the Terramare culture and was followed by the Etruscan culture, further exemplifies the problematic of representing transitions between cultures and their consequent time/space borders.

The problem of dealing with imprecision of time/space borders (Niccolucci, Hermon 2015b) can be addressed by applying principles of rough sets theory (Pawlak 1982). In presence of an imprecisely determined time set *A*, this approach considers two number sets *X* and *Y*, in our case two time intervals, with $X \subseteq Y$. *X*, called the core of *A*, is the largest (time) interval included in *A* during which the event occurs; *Y*, called the support of *A*, is the smallest (time) interval out of which the event does *not* occur. In other words, for times in *X*, the event takes place for sure; outside of *Y*, the event does *not* take place; nothing is known for times outside *X* but within *Y*. Such an approach is particularly applicable to archaeology in cases when the concepts of *terminus post quem* (TPQ) and *terminus ante quem* (TAQ) are adopted: *Y*, the support, is actually the interval between TPQ and TAQ.

A further solution for solving the problem of representing information on boundaries and their likelihood of existence is provided by the fuzzy set theory (Zadeh 1965), successfully applied to archaeology where uncertainty is involved (Crescioli *et al.* 2002; Hermon, Niccolucci 2003; Hermon *et al.* 2004; Farinetti, Hermon, Niccolucci 2010; see also Baxter 2009; Jaroslaw, Hildebrandt-Radke 2009; Popa, Knitter 2015). Reasoning usually implies Boolean logic, deciding the truth or falseness of some statement,

or equivalently the belongingness (or not) to a specified set. Instead, the fuzzy sets model concerns situations where there are several degrees of truth and belongingness. In this theory, sets have a belongingness function that assigns a number between 0 and 1 to every element x of a fuzzy set X: the value is zero if x definitely does not belong to X, 1 if x definitely belongs to X, an intermediate value if x possibly belongs to X. The approach is similar to the rough sets introduced above, with the important difference that for the "no-man's land" between belongingness and not belongingness (or, truth and falseness) it is possible to assign a measure to the degree of belongingness (or truth).

Although fuzzy sets might recall the probabilistic approach, it is fundamentally different and much more suitable for modelling uncertainty. Fuzziness addresses imprecise and vaguely defined statements; probability, on the contrary, deals with the as yet unknown truth of a precise statement, for example something due to happen in the future, which will either happen or not. The normalisation approaches recently proposed (Binding 2010; Doerr, Kritsotaki, Stead 2010) attempt to address this issue; motivated by the practical goal of dealing with information in digital systems, they may oversimplify the problem, at least conceptually, while fuzzy logic has sound theoretical foundations.

Apart from quantifying and formally representing the vagueness of positioning in time/space an archaeological culture (Niccolucci, Hermon 2015b), fuzzy sets theory may contribute in assigning a reliability index to the setting of an archaeological culture, based on the vagueness of its defining events. Such an index may be computed by averaging the reliability indices of each event defining the archaeological culture (Hermon, Niccolucci 2002). An archaeological culture is described by its defining archaeological events and their subsequent reliability indices, while their time-space borders are described through fuzzy logic. This seems to put the burden of quantifying fuzziness onto the component events, and indeed it is so. In this way, the research community may assess easier their reliability.

Several interesting questions rise: (a) Is there a prevalent event that determines archaeological cultures? In other words, what is the contribution of each defining event in determining the nature of archaeological culture? (b) How well we can determine the space-time borders of such events and how well these correspond to other events' borders? An immediate consequence to the above is that the sharper the definition of such events, within unique borders in time and space, the more robustly the archaeological culture is defined. (c) How many events are sufficient and enough to define an archaeological culture? The answer to this question is subjective of course and is set by researchers' choices. Whatever these may be, they have to be explicitly declared and accordingly motivated.

Another interesting consequence of such an approach (beyond the scope of this article) is the exploration of the nature of relations between events.

These represent the impact of various agents, such as social complexity, economic organisation, environment, sets of beliefs, etc. Moreover, they may contain information on how knowledge is transmitted between such events and how events influence one another. Thus, by exploring in depth the nature of such relations we are able to better assess the archaeological society under investigation and its inner social structure. Moreover, such an exercise helps verifying the consistency of our description of the given archaeological culture.

7. Discussing the space-time material culture relation as an identity criteria for archaeological cultures

A typical archaeological research looks at the material culture within a given space-time limit, identifies unique and characteristic identity criteria (Niccolucci, Hermon 2015b) and tries to give them a meaning (by typological, technological or related material sciences research). If, after a first iteration, no conclusive and robust identity criteria were isolated, the time-space borders are modified. Such iterations occur until a coherent set of identity criteria is isolated within meaningful time-space confines. A fundamental requirement standing at the basis of any construction of an archaeological culture is that the time-space-form relation maintains its structure and resists any attempts to change its delineation. In other words, if by changing the geographic extension or the time frame we find similar identity criteria in the analysed material culture, then we must reconsider the time-space-form relation. Therefore, archaeological identity criteria and their coherence in a given time-space are at the core of any construction of argumentation in archaeology (Doerr *et al*. 2011) and the success of identifying them correctly stands at the heart of any solid reasoning in archaeology. Thus, understating the relation time-space-matter and being able to formally present it are the foundations for any attempt at large-scale data integration within global knowledge repositories.

By attempting to formally describe an archaeological culture and its time-space relation, we may identify flaws in the construction of our reasoning process (Damnjanovic *et al.* 2013). Moreover, we can describe the triumvirate space-time-matter in terms of "robustness", "consistency" and "coherence". Reliability indices can be assigned to the defining events composing the archaeological culture and their time-space borders, which, consequently, will describe the robustness, consistency, soundness of our definition of archaeological culture and its positioning in time-space. Thus, the robustness degree of an archaeological culture indicates how well the time-space segment has been defined, based on the accuracy of dating, granularity of time and the preciseness of the defining events. The consistency index relates to the similarity of time-space-form relation among the defining events in various

time-space slots, within a given time-space segment, while the soundness index indicates the quality of the consistency, measured among the various archaeological events, within any time-space segment. These indices may be evaluated within the frame of fuzzy sets theory and indicate the quality of our definition of archaeological culture and how well it is anchored in time-space. Thus, the approach described above is instrumental in assessing how archaeological cultures are defined and to assess the quality of data used in such a construction.

8. Summary and conclusions

In this article we described an innovative approach for positioning in time-space archaeological cultures, based on rough sets and fuzzy logic. Such an approach is instrumental in disambiguation exercises, by clarifying common confusions between cultures and periods, or the geographic distribution of archaeological events. Moreover, we propose to use fuzzy sets theory based indices that help evaluating the nature of archaeological cultures, within their time-space borders and consequently the accuracy of their definition. We consider the present paper an introduction to future more detailed and in-depth work.

Disambiguation of terminology should relate not only to find matching between similar terms, but also look into how these terms have been defined, i.e. what are its identity criteria and how much they are reliable. The proposed above indices are instrumental in this exercise and should be a fundamental requirement for any preparatory work for setting-up large archaeological repositories and virtual collaborative environments. In fact, a wide use of data repositories and the re-use of digital data created by others require trust and confidence, as well as the knowledge of the limits that affect the creation of such data. It is not only the data, but also the metadata that make re-use possible. Such information about what is contained in a dataset, how it was collected, for which purpose, who did it and a measure of how much the creators (recommend to) trust their own data, are the pre-conditions to avail of the huge amount of information accumulated in years of digital archaeological data creation. Without this information such datasets are of little or no use: a human knows that putting the beginning of the Villanovan culture at 00:00, 1st January 1100 BC is silly; a computer does not.

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ABSTRACT

Locating archaeological cultures in time and space is a major challenge of archaeological research. Despite more than a century of scientific research in archaeology, a satisfactory solution has yet to be proposed. Past attempts to look into the problem focused on sharpening the definition of types of material culture artefacts, a more accurate chronological dating of such objects, various probabilistic methods or GIS solution for defining the time-space borders of archaeological cultures. However, the proposed approaches did not fully consider how the nature of archaeological cultures and their consequent dating and geographic positioning play a crucial role in assigning spatio-temporal borders. We propose to shift the operating logical paradigm in archaeology, from a crisp, Aristotelian-based logic, to fuzzy logic, in our opinion more suitable for reasoning in archaeology. We also introduce the rough sets theory to deal with chronological and geographic positioning of archaeological cultures. Both concepts have, in our opinion, substantial advantages over the traditional algebra and logic rules (implicitly) applied so far.