Connecting arrowheads: Differential transmission of information at the dawn of the Bronze Age

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Abstract:

The study of the relationships between prehistoric social groups is one of the main targets in present day archaeology. A useful tool to entangle this issue is social network analysis (SNA). Some of the advantages brought by this mathematic approach refer to the possibility of studying relationships through the material culture items, or its capability to integrate different scales of analysis (macro-micro). Moreover, SNA combined with the application of bayesian statistical methods of chronological attribution can create long range diachronic series of relational information, connected with prehistoric social groups dynamics. This methodology enables archaeologists to study archaeological big data from a totally different perspective, not only focused on a descriptive or morphometric point of view. The objective of this work is to apply an SNA procedure, together with a recently developed bayesian tool of chronological attribution, to archaeological sites located in the East of the Iberian Peninsula during the 4th and 3rd millennium cal. BCE using chert arrowheads as an archaeological proxy, due to the chronologic implications their morphology has, in the referred geographic frame. It is our specific target to analyse the transition between the Bell-Beaker world and the Bronze Age, through the differential transmission of information and the time-space variability present in the archaeological record, through the study of relationships between chert arrowheads assemblages. In order to do so, we will build a relational framework between the social communities present in the Late Neolithic-Copper Age through the chert arrowheads morphologic typologies, and we will apply SNA to characterize the resulting networks. Furthermore, we will propose a new metric to quantify the cultural fragmentation using community detection algorithms, in a diachronic axis, to identify groups of sites with homogeneous technological behaviour, to check the initial hypothesis which points to the existence of periods of cultural homogeneity followed by others in which fragmentation-regionalization is dominant.

Keywords: networks; chert arrowheads; social network analysis; Bronze Age; Copper Age

1. Introduction

The aim of this work is to analyse the differential transmission of information during the transition of the Late Neolithic societies, to the Bronze Age. This time span is crossed by the Bell-Beaker phenomenon, which is thought to represent a pivotal moment in Western Europe's information flows. It is our intention to study the potential existence of

Journal of Lithic Studies (2024) vol. 11, nr. 2, 24 p. DOI: https://doi.org/10.2218/jls.7256

Published by the School of History, Classics and Archaeology, University of Edinburgh
ISSN: 2055-0472. URL: http://journals.ed.ac.uk/lithicstudies/

homogeneity-fragmentation phases through the study of chert arrowheads artefacts and the social networks associated with their usage, configured following a similarity criterion. We have employed the chert definition provided by Hallsworth & Knox (1999). Social networks are as old as humanity and they are the complex structure in which biological and cultural trajectories of human population are shaped, conforming a dense web of relationships. In this context, network science provides a methodological paradigm that allows the characterization of social frameworks. Under this methodological umbrella there is a tool from the field of social sciences called social network analysis (SNA from now on), which serves precisely these purposes (Reynoso 2011). This research will highlight the great potential of the SNA as an analytical tool applied to chert tools (more specifically chert arrowheads) that are a characteristic item of the Copper Age in the Iberian Peninsula which. As it will be discussed later, due to their nature, they can be a good indicator of the information circulation circuits between the communities of the 3rd millennium BCE.

A diachronic analysis was carried out over a time bracket of 1500 years (5300-3800 cal BP). It will allow us to obtain a clearer idea of the evolution of social interaction networks. There are four cultural periods that can be easily recognized:

- 5300-4800 cal BP Late Neolithic.
- 4800-4200 cal BP Copper Age, which is divided in two subphases:
  - 4800-4550 cal BP Copper Age (Pre-Bell-Beaker).
  - 4550-4200 cal BP Copper Age (Bell-Beaker).
- 4200-3800 cal BP Early Bronze Age.

Climatic proxies point out to an aridification trend that can be seen throughout the peninsular Mediterranean façade, from *ca.* 5300 cal BP until 3200 cal BP, which reaches its maximum in the 4.2K event, with a global impact although geographically variable (Brisset *et al.* 2020). As works carried out in the Pego marshes (Alicante) indicate, the effect of this event on the peninsular Mediterranean coast is evident in the erosive dynamics of the soils previously degraded by human activities (crops and grazing), in which it is possible to appreciate a decrease of activity from 4800 cal BP. Moreover, data from various markers, such as marine n-alkane records, or speleothem records, also suggest a series of rapid transitions *ca.* 5300, 4800, 4440 and 3800 cal BP, in the Southeast of the peninsula (Hinz *et al.* 2019; Hinz *et al.* 2019).

Moreover, the demographic models implemented for this period in previous works paint an unstable panorama, that fit into a logistic growth model. The extensive radiocarbon series considered indicated the existence of a general upward demographic trend for the entire period in which there are three turning points (Bernabeu *et al.* 2018; Jiménez-Puerto 2022: 123–131): a rapid increase after *ca*. 5300 cal BP, which is followed by a stabilization phase. A rapid rise *ca.* 4,800, followed by another phase of slight decline between 4,500 and 4,200 cal BP. And in the transition to the Bronze Age, a period of sustained increase *ca.* 4300-3900 cal BP. Therefore, all evidences suggest that despite the climatic pulses and an increasing degradation of the landscapes, the demographic trend follows a growing pattern that can't be dodged. In that apparently contradictory scenario, the study of the social relations between Late Neolithic communities can provide a new approach vector to the problematics associated to the period.

1.1. Social Network Analysis

Although the origin of the SNA dates back to the 1930s (Freeman 2004), it has been throughout the decades of 1970, 80 and 90, that the methods of the SNA were formalized in a series of works (Burt & Structure 1991; Carrington et al. 2005:1-8; Freeman 1978), but their scope wasn't fully unravelled due to the lack of sufficient computing power. This aspect has been formulated in the work of Wasserman and Faust (1994: 725-733), and highlights the difference between the SNA and other network-based approaches. One of the reasons why the SNA is interesting in Archaeology is because it allows the integration of the concepts of agency and structure (Giddens 1979: 49-95). These two concepts have implications, in social science, that go far beyond the structural scale (Knappett 2011), but they are not the only reasons to use SNA. This methodology enables archaeologists to study aspects that other methods can't and they are useful to analyse hypothesis about relational sphere. Nevertheless, they shouldn't be considered as substitute of the classic archaeological research but a series of complementary techniques that force the researcher to think in the relations and their implications (Brughmans 2013; Knappett 2013).

Network analysis can be applied to the study of very diverse relational structures among which are the interactions between prehistoric individuals or groups. Those structures are re-enacted from the archaeological record which is often sparse and chronologically aggregated, embodying a tiny proportion of the communities that produced them. Social networks have a direct relationship with material culture since the teaching and training required to produce artefacts takes place eminently in the social sphere (*e.g.*, Derex & Boyd 2016; Derex *et al.* 2018; Kolodny *et al.* 2015; White 2013), for which the patterns of social interaction of the communities of the past are responsible of the formation of the material. Thus, it can be stated that material culture is the result of the interactions of spatial network systems, social learning and information exchange (Boyd & Richerson 1988: 32-79; Cavalli-Sforza & Feldman 1981: 10-15; Meskell & Preucel 2008; Renfrew & Shennan 1984; Shennan 2002: 2-45). In addition, the variations in the patterns of change of the artefacts considered by Archaeology are probably linked to structural alterations at the network level. Through the SNA it is possible to characterize this network structure, obtaining relevant information on the way in which information circulates. The SNA procedures allow the application of an extensive sample of mathematical metrics, which enable the quantification of the system's interactions. These metrics can be structural (macro level), meso level (communities) or individual (micro level) (Rivers 2016), and will be discussed in more depth in the next chapter.

2. Material and methods

2.1. The use of arrowheads as proxy for social interactions

The convenience of using material culture as a social indicator has been supported by many previous works (*e.g.*, Marsden 1990; Shennan *et al.* 2015; Turner & Maryanski 1991; White 2013). We will assume that the similarities between pairs of sites are an indication of the probability of interaction between them and will be quantified through material culture similarity indices (Borck *et al.* 2015). In our particular case, the lithic arrowheads have been used as indicators of the nature and intensity of social relationships. There are ethnographic and typological related studies that justify the use of projectile points as an indicator of social interactions (*e.g.*, Wiessner 1983; Wiessner 1984; Wobst 1977). It is our assumption that these elements of material culture are potentially representative of the information flows between the communities. The transport and exchange of raw materials or prestige objects is also a proxy for social interaction (Newell 1990; Riede 2014; Maier 2015). However, lithic arrowheads and transported goods represent social interactions at different levels. As long as we have no evidence to think on long-distance chert exchanges, and chert sources are relatively accessible by locals on every corner of the Mediterranean façade of the Iberian Peninsula, is reasonable to conclude that, to craft chert arrowheads the only requirement is the concept itself or the technique. For this reason, its distribution must be linked to existing social interaction networks.

The most common criteria employed to select the material culture samples are:

- Frequency: the selected items must have a sufficiently broad presence in the registry so that it does not result insignificant by default (very limited or few items), or by excess (an artefact present throughout the temporal and geographic range) at the time of establish relations.
- Diversity: the selected items must present a certain comparable formal diversity.
- Representativeness: the artefacts must be representative of the different chrono-cultural moments analysed in this work or of some cultural group present in the geographical and chronological scope chosen for the work.
- Previous systematizations: that there are previous classifications or typologies that allow them to be characterized (Bernabeu 1979; Juan-Cabanilles 2008: 129-153).

As they fulfil of these requirements in our diachronic and geographic framework, chert arrowheads represent a perfect element to be considered for analysis.

The chronological range was set in the bracket 5300-3800 cal BP. The choice was made following archaeological reasons: although chert arrowheads can be already found in early phases of the Neolithic, is the Late Neolithic and Copper Age, when they are extensively present in the register. At the same time, they show a high degree of chronological and geographical variability (Juan-Cabanilles 2008: 135). Thus, lithic arrowheads, both due to their variability and their abundance, are a suitable cultural item to carry out this analysis. The information of each individual site has been extracted from monographs, compendia and articles referring to the material culture of the excavated sites, and can be traced in a database published in Zenodo repository (Jiménez-Puerto 2022a). The classification of the arrowheads is based on seven types (Figure 1) following the morphological criteria which we briefly describe below:

- Type 1- Rhomboid or rhombus eye
- Type 2- Cruciform or with side appendages
- Type 3- Leaf-like
- Type 4- Peduncled without barbs
- Type 5- Concave base
- Type 6- Asymmetric
- Type 7- Barbed and tanged

The sample used in this work is very diverse in nature, both chronologically and geographically. Archaeological investigations suggest that the forms, decorations, materiality or symbolic content of some artefacts can be related to certain spatially and chronologically defined social units (White 2013; Shennan *et al.* 2015). For this reason, a selection of archaeological levels that contain lithic arrowheads was performed, in order to serve as indicators of the social relations of the 3rd millennium BCE.

The geographical scope chosen includes the Mediterranean façade (central-southeast) of Iberia, which includes the hydrographic basins of: the Júcar, the Segura, the Almanzora-Andarax, and the tributaries of the Ebro river: Guadalope, Martín and Cérvol. This coincides, to a great extent, with the geographical scope delimited by the provinces of Castellón, Valencia, Alicante, Murcia, Almería, Albacete, Cuenca and Teruel (Figure 2). Traditionally, an invisible frontier has been suggested that would define two areas of influence: the Júcar River (Tarradell 1965; Picazo 1993; Gil-Mascarell 1995; Barrachina 2012: 184-189). These two zones of influence (northern and southern) are clearly watchable in the material record, although possible problems of research bias cannot be completely ruled out either. In addition, data from deposits in the neighbouring provinces of Madrid, Zaragoza, Tarragona and Granada have been incorporated, used to avoid the creation of artificial borders in the geographic frame, and consider the connections with outer circuits.

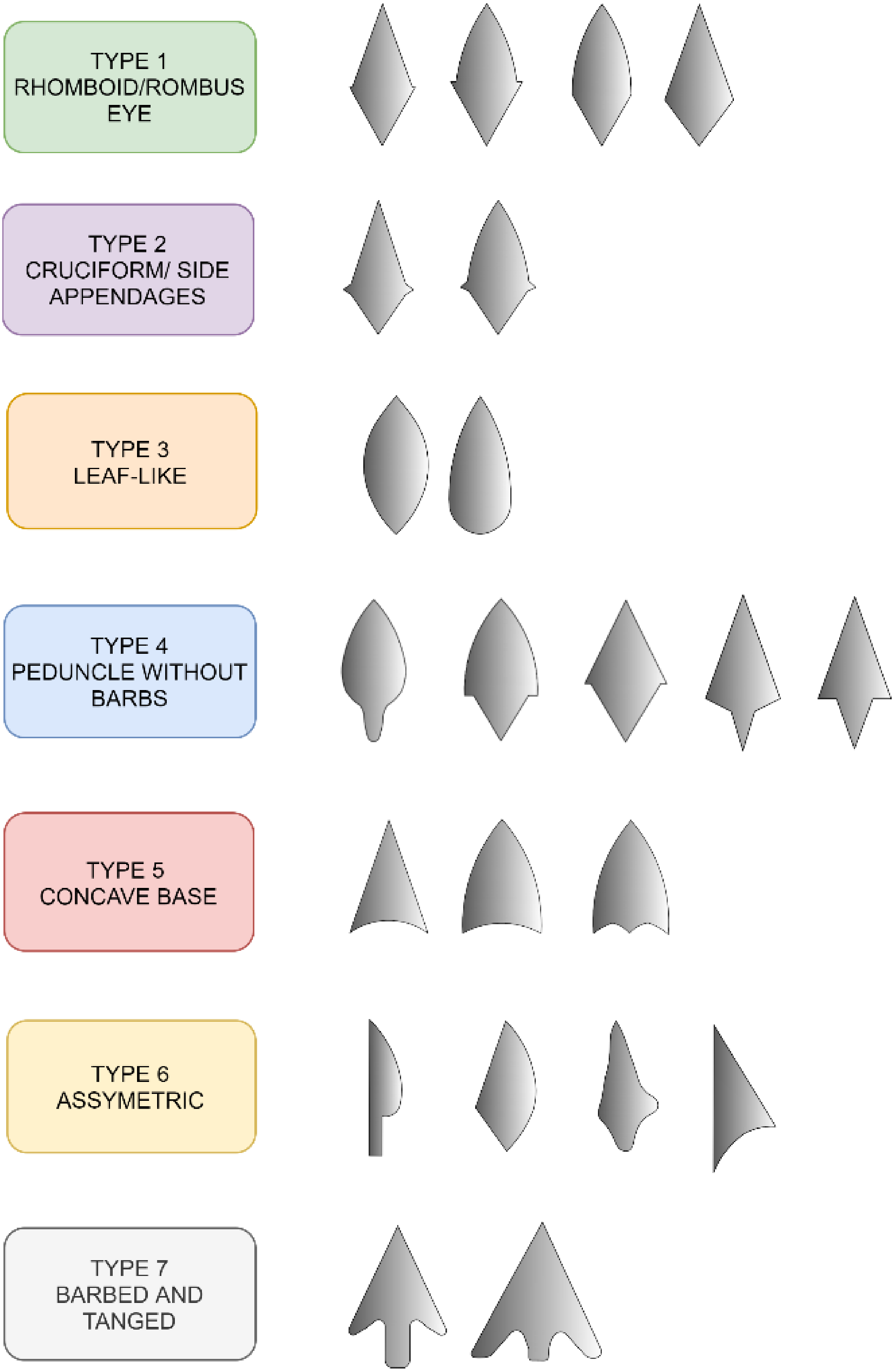

Figure 1. Main arrowhead types used in this analysis.

As far as the distribution of the lithic arrowheads is concerned, we observe that there is a differential geographical presence of various types. Thus, the points with a concave base are circumscribed to the region that extends south of the Júcar. All of them are under the Los Millares aegis and their chronology corresponds to the end of the 4th and beginning of the 3rd millennium BCE. Something that can also be observed in the asymmetric tips. The points with the most uniform extension are the pedunculated and the finned, which are present in all the sub-basins and whose chronology is tilted towards the second half of the 3rd millennium BCE. Again, the largest proportions occur in the southern basins. Of wide geographic extension are also the cruciform, leaf-like and rhomboid points with a potentially older chronology (end of the 4th-half of the 3rd millennium BCE). The scarce entity of the northernmost basins in terms of absolute frequencies could be derived from a lower geographic density in these areas, although it is also possible that it is derived from a different state of the researches. As can be seen in Figure 3, the collections from the basins south of the Júcar River contain a greater space-time variety, so it can be advanced that the cultural groups of the South participate in more diverse and assorted exchange relationships. than the northern groups.

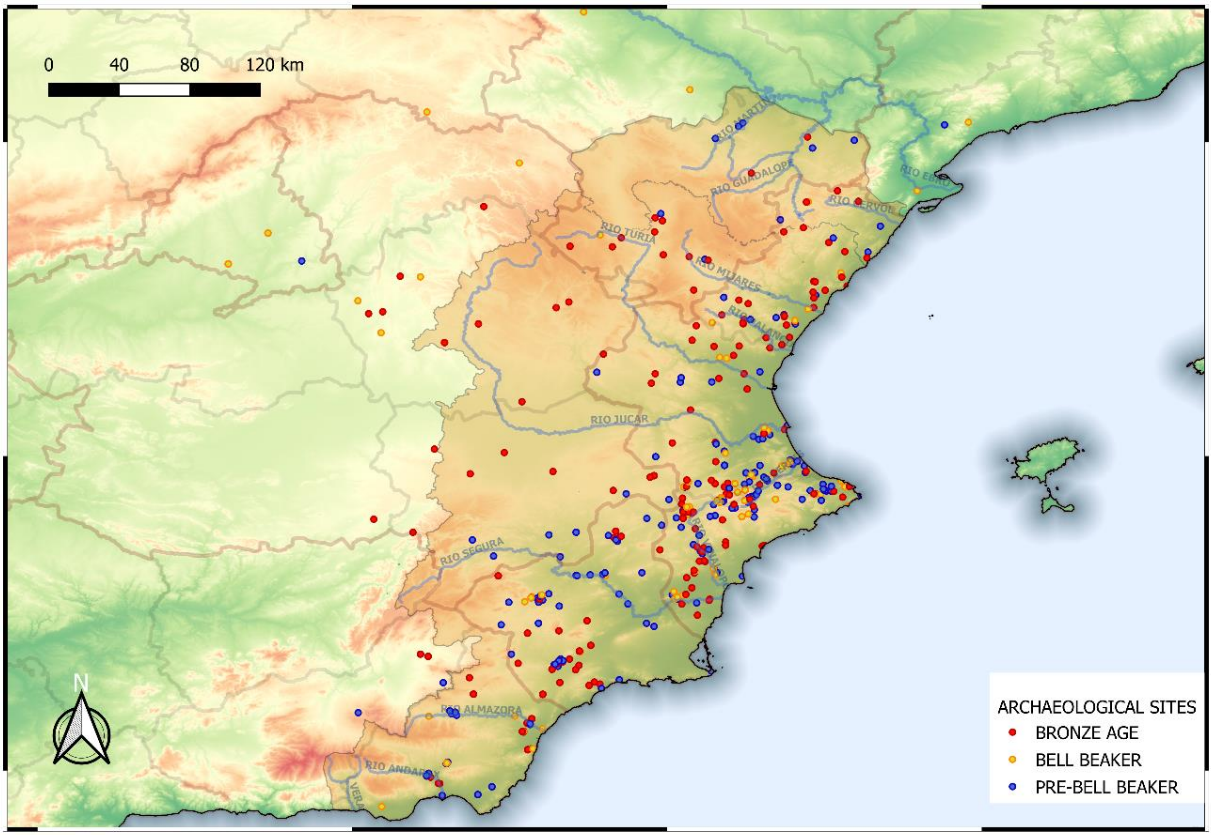

Figure 2. Map of the region with archaeological sites.

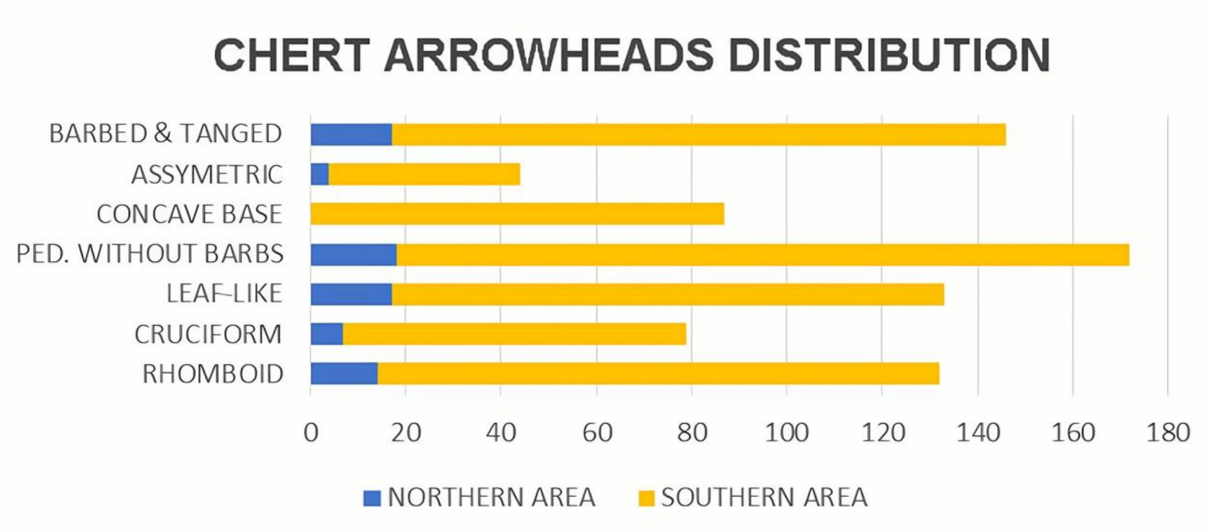

Figure 3. Counts of chert arrowheads in the two areas divided by the Júcar river basin.

2.2. Network construction

To perform the analysis, we need to organize the data and localize the archaeological levels in time and space. We have used the geographical coordinates of each site, using EPSG 4326. The chronological attribution has been more complex. Although each material context has been attributed to one of the cultural periods (Late Neolithic, Copper age, Bronze age), which allows acquiring a first view of its distribution throughout the sequence, it has been decided to divide the time period into temporary windows of a fixed width, in our case 150 years. This duration has been established after trying with lower, (which resulted in many redundant windows) and higher values (no evolution could be traced). All of these issues come from the resolution of the existing radiocarbon series, which prevent a more accurate approach. The resulting time windows correspond to the chronological periods expressed in Table 1. Once determined, the next step consisted in attributing the dated levels to one or more windows. In this section, a selection and filtering criterion for 14C dating has been employed (Bernabeu *et al.* 2018). The radiometric information has been taken from various repertoires (Balsera *et al.* 2015; Salas Tovar *et al.* 2016; Pardo-Gordó *et al.* 2020).

Table 1. Definition of time windows and their equivalencies together with cultural periods.

Window	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Chronology cal BP	5300-5150	5150-5000	5000-4850	4850-4700	4700-4550	4550-4400	4400-4250	4250-4100	4100-3950	3950-3800
	Late Neolithic			Copper Age				Bronze Age		

Those levels that have been determined chronologically by associated 14C dates, that meet the criteria, (that is short-lived precedence and an SD<100), and have been directly attributed with an algorithm developed *ad hoc*. This process has been implemented in a script, called CHRONARCH, using the R language R 4.0.3 (R Core Team 2017), which can be a very useful tool in radiocarbon-based archaeological analysis and has been published in an open-access repository (Jiménez-Puerto 2022b). The developed algorithmic procedure begins by calibrating the dates using the intcal20 calibration curve (Reimer *et al.* 2020). After, each calibrated date was assigned to a specific window if at least 40% of the HPD area falls within the interval of that time window.

In addition, archaeological levels without radiocarbon determination, whose associated material culture is relevant, have been included following a recently published Bayesian procedure (Pardo-Gordó *et al.* 2022). This procedure allows deposits to be located chronologically based on the material culture of well-known contexts that have 14C, thus being able to substantially increase the existing sample.

Once the chronological attribution procedure has been completed, the data formatting phase begins with the shaping of the different networks. It is necessary to convert the archaeological data to relational matrices following similarity criteria. For this, the Jaccard similarity index (Jaccard 1912; Liu *et al.* 2016) has been used, which is especially suitable for this case because it is based in the presence or absence of types (Jiménez-Puerto 2018). The similarity values provided by Jaccard must be normalized to avoid bias in the results derived from changes in the number of types present in the different chronological windows following a procedure already explained in previous works (Bernabeu *et al.* 2017).

Next, the networks corresponding to each time window were composed with the relational information. The nodes in the network represent the sites and the links represent the similarity. Note that the links intensity is weighted by the similarity value. In this case, the networks layout has been configured using the coordinates from the sites to locate the nodes. For visualization, the Gephi Geolayout plugin (Jacomy 2011) has been used, to provide networks positioning against a map. Once the networks have been created for each time window, the metrics that (network size, density and clustering) were calculated using the Gephi program (Bastian *et al.* 2009).

2.3. Metrics employed.

In this study an SNA was performed, to obtain a series of metrics. The analysis focuses on the macro and meso level, being the micro level only employed for the visualizations. The macro level metrics are:

- The number of nodes: it will indicate the number of entities present in the network, providing an idea of its size. In this case the actors will be archaeological sites.
- Density: indicates how dense is the network of contacts between nodes. High values indicate great connectivity and relationships between actors, while low values indicate the opposite. These cohesive groups are called clusters, although when a network is very dense it is difficult to observe clear clusters.
- The clustering coefficient: indicates the number of triangles in a graph and is related to the transivity of a graph. It provides a quantification of the degree of structural cohesion of the network. High levels of cohesion stimulate social stability as grouping reinforces association and trust in social exchanges. It can be useful to give an idea of the resilience of the network to external disruptions and therefore of its stability or robustness (Watts & Strogatz 1998).

The meso (intermediate) level metrics provide information about the groups of the network, and enable the implementation of a new metric based on community recognition algorithms. Community detection operations are very useful to classify and label data, to carry out complementary analyses to centrality measures, and to find the centres of gravity of the network, thanks to the fractal and homophilic properties of networks. These methods have been widely used in SNA, developing different proposals (Girvan & Newman 2002; De Meo *et al.* 2011; Fortunato 2010) The Leiden method proposes a community detection procedure (Traag *et al.* 2019), which we will use in this work to propose a new metric to quantify the cultural homogeneity of a system based on networks of similarity.

Finally, in our case, the individual metrics will grant an easy reading of the graphs of each window, obtaining a general idea of the role that each node plays in the dissemination of information. The layout is based on two metrics:

- The degree: expresses the number of connections that a node has. In social networks you can quantify the probability of receiving information.
- The betweenness centrality: it is a measure of the relevance that a node plays in the information traffic, in terms of intermediation. It can also be understood as an indicator of those nodes that perform bottleneck functions.

2.4. Analysis of cultural homogeneity through a new metric: Fragmentation ratio

A community is a property of networks in which a group of nodes shows a higher density of connections among themselves that between them and the rest of the nodes. A structure in which these communities are weakly connected (or even disconnected) to the rest of the network could influence the transmission of information between communities by preventing a rapid and fluid transmission of ideas. Community detection algorithms serve to detect those cliques that are relatively independent within a network, perform similar functions or are internally cohesive (Fortunato 2010). Here we propose a new metric that contains great potential to quantify the fluidity of the information flows between groups and therefore the cultural homogeneity using the Leiden algorithm (Traag *et al.* 2019). It was based on the following premise: the presence of windows in which the network is divided into many groups, should be indicative of potential periods of fragmentation. Our initial hypothesis considers that, for periods of cultural homogeneity, the Leiden algorithm produces few large communities and for moments of fragmentation many smaller communities. In a first step, it was thought that the ratio between the number of communities and the number of total nodes in a given window could be a good indicator. However, we soon realized that this ratio did not take into account the size of these communities, so in the case of a huge community and many tiny communities, it could be biasing the result. For this reason, we decided to multiply this value by a correction factor that takes into account the size of the communities provided by the Leiden algorithm. This factor will represent the percentage of nodes in the smaller communities.

$$H = {}^{C_T}\!/_{N_N} \cdot (1 - C_G)$$

Where C_T is the number of Communities found by the Leiden algorithm, N_N is the number of nodes present in that windows and C_G is the biggest community.

Therefore, the Fragmentation ratio metric, developed in this work, quantifies the homogeneity-fragmentation of a certain window, taking into account the size of the communities detected and that of the total network. On the other hand, the definition of these communities is determined by the researcher's choice of initial parameters for the Leiden calculation. Nevertheless, it is necessary to warn that this metric can be useful for the sort of networks we are working with, but might change for other kind of archaeological networks. Our proposal suggests that the parameters used should always be explicit to guarantee reproducibility. In order to assess its possibilities in detecting cultural boundaries, the Constant Potts model (Dorogovtsev *et al.* 2004) has been used with the following parametric adjustments: a resolution of 0.13, 100 iterations, 10 restarts and random seed. Moreover, the parameters should be tuned up by looking for the highest coefficient of goodness in the determination of the communities (something that the Leiden algorithm always shows), but trying to adjust the communities detected to those provided by the visualization algorithm Yifan Hu (Hu 2005). The reason why we propose Yifan Hu layout as a tune up tool is related to the fact that it always looks for the groups with the strongest connections. However, it is important to point out that this part is the most sensitive and is where the most precautions should be taken. It is at this point that the available archaeological information is decisive, having the last word in the validation of the results.

3. Results and Discussion

The lithic arrowheads have an almost constant presence in the material record of the 3rd millennium until its final phase. Table 2 shows some trends in network density, clustering, and size (nodes) over the course of the 5300-3950 period, when the arrowhead-based network virtually disappeared. However, the normalized density values are significantly higher than the clustering, which could be an indication of a greater cultural homogeneity and resilience (Figure 4). This is clearly seen in the 4850-4700 window, in which, despite being a time of crisis, the network based on lithic arrowheads maintains a relatively stable density. The chert arrowheads have their moment of greatest diffusion in the period 5150-5000 (Figure 5), which matches with a moment of great growth of the network and homogeneity in the material culture.

Table 2. Main metrics values.

Chronology cal BP	5300-5150	5150-5000	5000-4850	4850-4700	4700-4550	4550-4400	4400-4250	4250-4100	4100-3950	3950-3800
Nodes	40	91	26	30	63	32	27	21	31	21
Density	0.703	0.744	0.52	0.52	0.646	0.585	0.558	0.567	0.359	0.376
Clustering	0.801	0.847	0.778	0.79	0.865	0.861	0.867	0.802	0.808	0.906

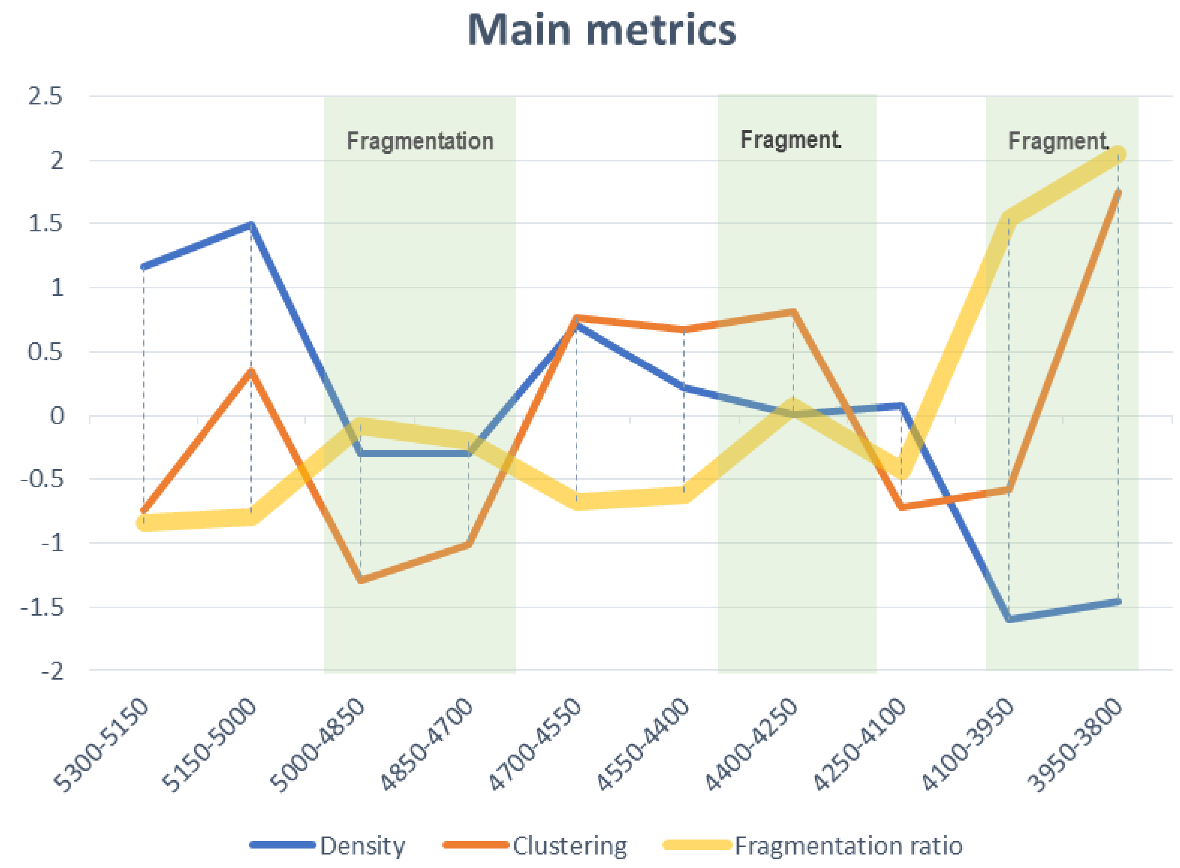

Figure 4. Fragmentation ratio, clustering and density normalized values

The other moment of greater extension of the networks of lithic points takes place in 4700-4550. This is a moment of great uniformity in the archaeological register, which

 DOI: https://doi.org/10.2218/jls.7256

coincides with the appearance of the Bell-Beaker phenomenon. It is a moment of high values of density in the graphs and low values of the fragmentation ratio, which lasts until the next window (4550-4400) (Figure 4). It is possible to associate the presence of some specific typologies to some periods. While the foliate and rhomboid tips have older chronologies (Late Neolithic), the peduncle and fin tips are highly in tune with the Bell-Beaker phenomenon (Copper Age). Some types also have a clear geographic localization, so that the concave points are clearly associated with the orbit of Los Millares and are circumscribed to the southern part of this study (Armero *et al.* 2020). At 4400-4250 the chert arrowhead-based network, as can be seen in the size of the network (Table 2) and all metrics start a downward trajectory. In the next window an interesting phenomenon takes place related to an increase in clustering, while the density remains stable. This could be an indicator of the existence of regionalization processes and therefore of less circulation of information. As can be seen in the graphs of this moment, the northernmost area maintains a certain internal cohesion, while the southern area is more disconnected. This fact is probably an indicator of the existence of different internal dynamics for the northern basins, in which the inertia produced by the preceding social trajectory would be maintained for longer than in the South. This is reflected in the graph, since the grouping suffers a large drop, while the density is maintained, which indicates the great internal cohesion of the remaining groups at this time.

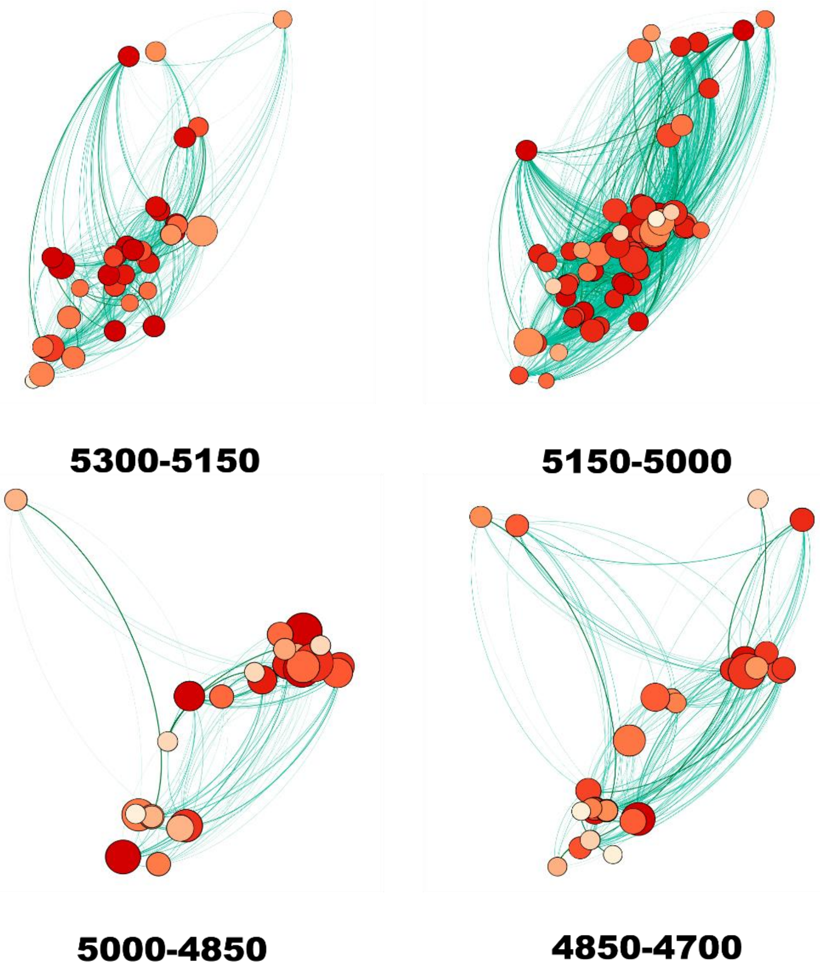

Figure 5. Graphs from the period 5300-4700. The colour of the nodes indicates the degree, their size indicates the betweenness centrality. The intensity of the edges indicates the strength of the relationship.

From the period 4250-4100 the density falls, a trend that is maintained until the end of the series, when the network based on points disappears from the Southeast, leaving a reduced and highly connected community in the northern part (Figure 6). This fact is not surprising since the northern sub-basins have a lower average accessibility, due to the proximity of the Iberian System. Thus, the more geographically isolated, the less likely it is that the system will evolve, since isolated groups have greater cultural inertia, incorporating innovations at a slower pace (Alderman 2012). From the 4700-4550 window, the chert arrowheads networks begin a gradual decline that will largely determine the behaviour of their metrics. In the crisis period of 4400-4250 they maintain a certain stability, although they also show symptoms that point to the existence of a more fragmented world. This disintegration will continue until the disappearance of the chert arrowheads from the material record in the last window. Note that it was detected a small prevalence, which comprises mainly the communities to the North of Júcar river, in the 4100-3950 cal BP period.

In addition, small-world effect can be also seen in Table 3. This table present the crossing of two metrics traditionally associated with small-world structures: clustering and average path length. To be able to speak of such situation the clustering coefficient has to be high and the average path length must be low (Watts & Strogatz 1998). A small-world topology can have a great impact on properties of the graph. In small-world graphs only takes a few short-cuts between neighbour communities to turn a large world. The resulting networks have unique properties of regional specialization with efficient information transfer (Telesford *et al.* 2011).

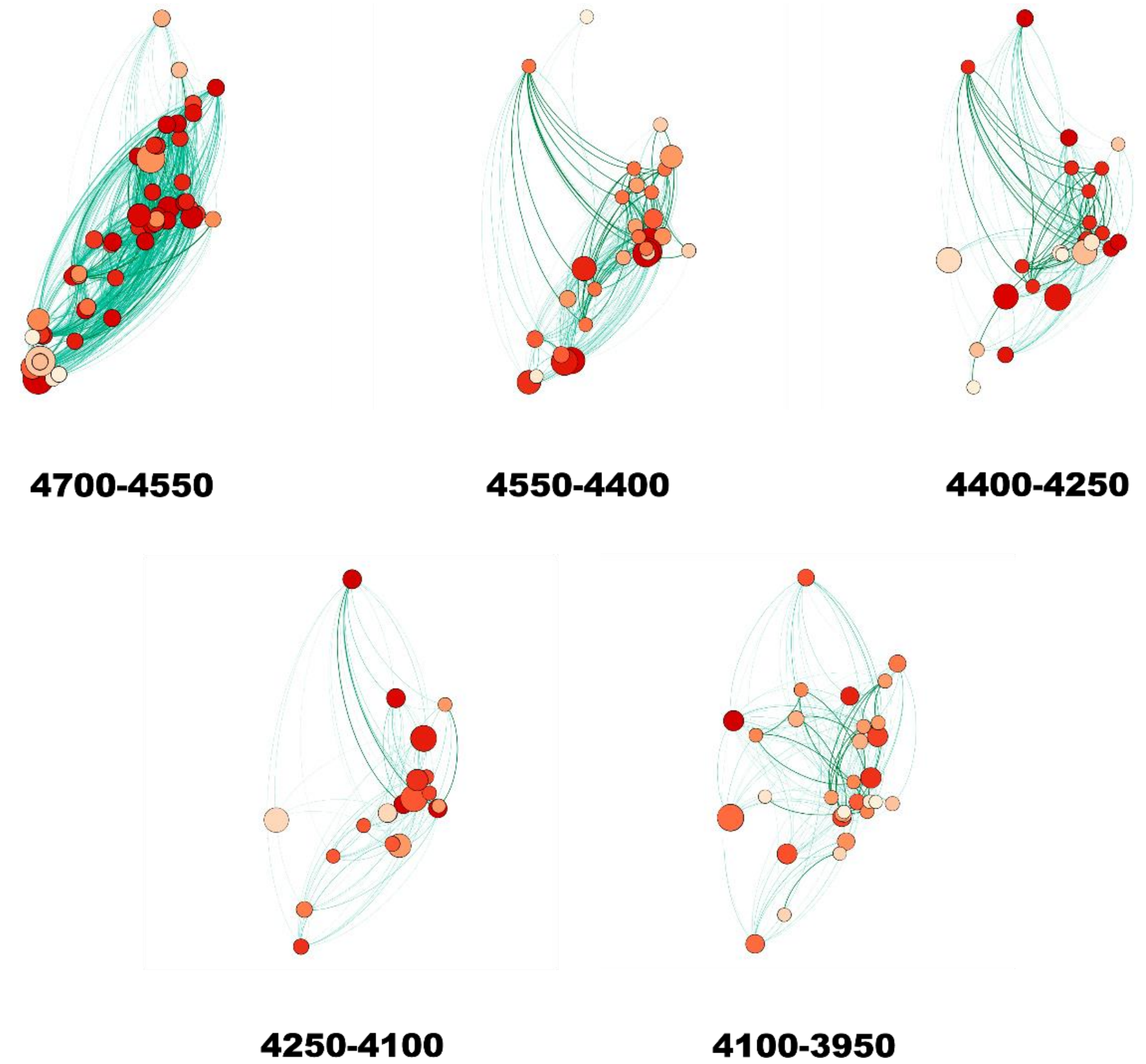

Figure 6. Graphs from the period 5300-4700. The colour of the nodes indicates the degree, their size indicates the betweenness centrality. The intensity of the edges indicates the strength of the relationship.

Table 3. Values for clustering coefficient and average path length.

Window	5300-5150	5150-5000	5000-4850	4850-4700	4700-4550	4550-4400	4400-4250	4250-4100	4100-3950
Clustering coeff.	0.788	0.839	0.691	0.74	0.847	0.780	0.887	0.803	0.69
Av. Path length	1.298	1.255	1.510	1.403	1.363	1.417	1.509	1.471	1.702

In the table we can see the higher clustering values in yellow, while we see the lower average path length in orange. There are only two windows (2nd and 5th) in which both occur at the same time. The first period detected corresponds to the final of the Late Neolithic cultural phase, which will lead to the Copper Age in the following window. The second one is related to the beginning of the early Bell-Beaker phase, which is characterized by the so-called International styles, that can be found almost everywhere in Western Europe (Lemercier 2018). Therefore, this small-world effect can be found in windows 2 and 5 which have been signalled as moments of greater homogeneity by the fragmentation ratio (Figure 4).

3.1. Recognition of communities and Fragmentation ratio

The result provides an average quality of 61% for the ten windows, which is acceptable for the provided resolution. The visualization of the results obtained from the Leiden algorithm provides graphic and intuitive information on the diachronic evolution. The fragmentation ratio informs about the relevance of the detected communities in relation to the rest of the network. Thus, notice the difference between a window in which there are 3 communities, and the largest community is shaped by 95% of the nodes present in that network; and another window in which we have the same number of communities (3) but the number of nodes in each community is distributed evenly (that is 33% of the total each). In the first case, the fragmentation value will be lower, and in the second higher. The table below (Table 4) shows the data obtained and the resulting fragmentation ratio, calculated according to the procedure explained in the methodological section. Likewise, the result has been drawn in Figure 7 and will serve as a quantifier of the degree of homogeneity-heterogeneity. Figure 8 shows the communities obtained, which have been organized spatially using the "Yifan Hu proportional" algorithm (Hu 2005), so the previously presented geographical situation is left aside and the nodes that make up the community are grouped together to make it more visible (with a different colour code for each window). Each node has a number that serves as an identifier which can be obtained from the data base in supplementary material.

Table 4. Calculation table for the Fragmentation Ratio.

Window	**5300-5150**	**5150-5000**	**5000-4850**	**4850-4700**	**4700-4550**	**4550-4400**	**4400-4250**	**4250-4100**	**4100-3950**
N. Leiden comm.	2	2	5	4	4	2	4	3	6
Total n. of nodes	40	91	26	30	63	32	27	21	31
N. of nodes in the biggest comm.	39	77	21	23	54	26	19	18	13
Fragmentation Ratio	0.0012	0.0034	0.0370	0.0311	0.0090	0.0117	0.0438	0.0204	0.1124

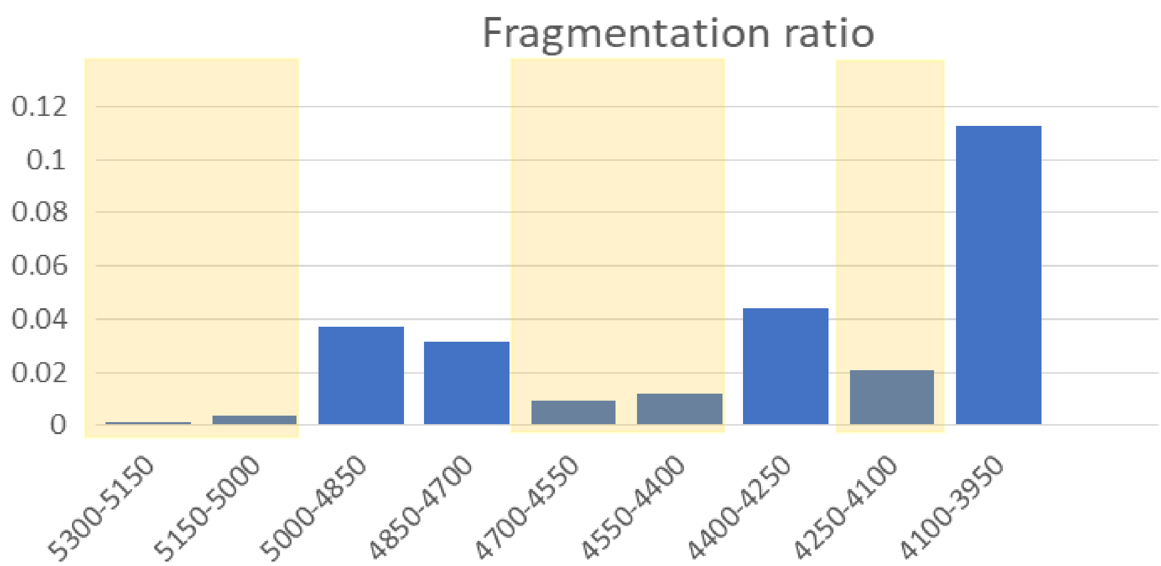

Figure 7. Fragmentation Ratio for lithic arrowheads.

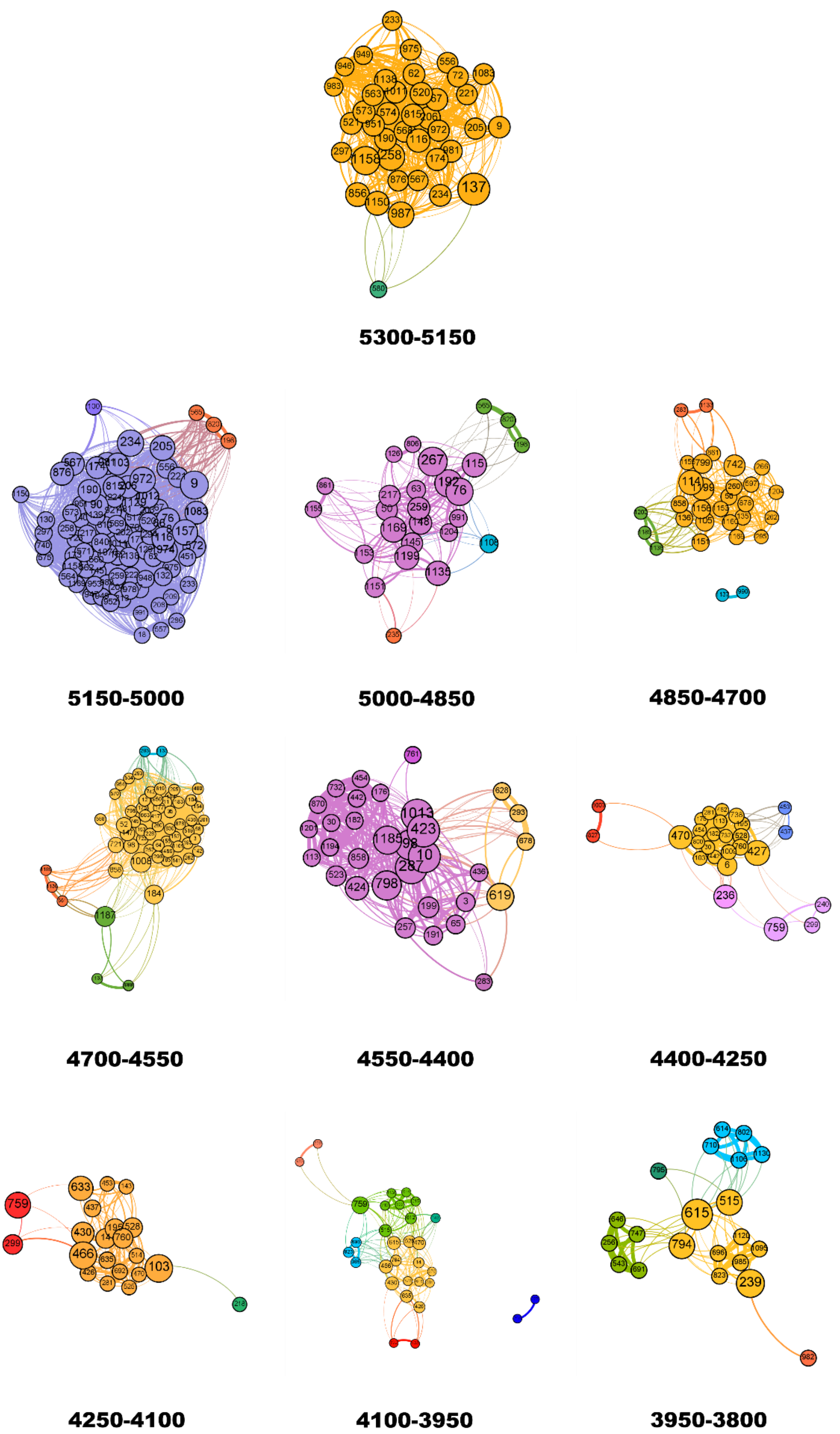

Figure 8. Graphs of the communities recognized with the Leiden algorithm, for networks on total lithic points, distributed with the YiFan Hu algorithm. The color indicates belonging to a community. The size the betweenness centrality.

Three phases emerge in which lower fragmentation is observed. These periods, 5300-5000, 4700-4400 and 4250-4100, coincide with the initial phases of the Los Millares site, with the initial Bell-Beaker stage and with the beginning of the Early Bronze Age. Three periods of greater fragmentation are also observed (5000-4700, 4400-4250 and 4100-3800). It is necessary to mention that this panorama of fragmentation in the last part of the chronological series also coincides with the gradual loss of the presence of lithic arrowheads in all areas, with the exception of a densely connected core in the Sistema Ibérico, with a great cultural inertia, probably related to higher geographic isolation.

The homogeneity-fragmentation phases detected are highly consistent with the available context-based information (*i.e.*, stratigraphy) and are clearly aligned with the archaeological knowledge available for the period. So, it can be stated that the results provided by the Leiden algorithm for the detection of communities and the data provided by the new metric of the Fragmentation ratio on networks of lithic arrowheads are congruent with what was observed in the structural metrics and allow us to be optimistic in relation to future applications to quantify homogeneity-fragmentation phases in some archaeologic environments.

Some genuine concerns raise up around the way the decision about the parametric adjustments is made. Here we propose a series of good practices which include the publication of the pre-sets used, to ensure the robusticity of the ratio and the replicability of the experiment. Finally, the open access publication of the data is recommended as keeping the transparency must always be a priority for the scientific research.

4. Conclusions and future perspectives

The objective of this work was to apply an approach based on the social networks analysis, together with the development of a new metric to quantify cultural periods of homogeneity-fragmentation and assess the impact of the dissemination of information to the communities located in the East of the Iberian Peninsula during the 4th and 3rd millennium cal. BCE, using bifacial chert arrowheads as an archaeological proxy.

There is one feature that can be highlighted for the 3rd millennium *sensu lato*: its unstable nature. The demographic growth, indicated in other works seems continuous during the time series and fits well in a logistic growth model (Bernabeu *et al.* 2018; Blanco-González *et al.* 2018; Hinz *et al.* 2019). Moreover, it can be noticed the existence of sudden jumps in the size of the network, analogue to those found in the previously cited prehistoric demography works. These periods which were discussed in more depth in other works (Jiménez-Puerto 2022c) are: *ca.* 5300, *ca.* 4700 and *ca.* 4100 cal BP. The second coincides with the previous moment to the Bell-Beaker phase, and the second with the dawn of the Bronze age. On the other hand, the structural metrics (graph 5) clearly indicate two critical moments corresponding to window 3 (5000-4850 cal BP) and 8 (4250-3950 cal BP), which match quite well with the values indicated by the proposed brand-new fragmentation ratio. Although both crises are similar in their features, they noticeably differ in their impact on the network. After the first crisis the system seems to recover quickly and the impact on the fragmentation is low. On the contrary the second crisis shows a period where the information flows with difficulty, opening a moment of higher fragmentation with communities redirecting their relations to the core (small worlds) and bonded with the others by weak ties. It mainly affects the dissemination of information and influences the conformation of communities that announce the subsequent differentiation between the archaeological entities of the Argar, to the South, and the Valencian Bronze, to the North. Chert arrowheads will be gradually abandoned and be replaced by the copper points and weapons, disappearing from the archaeological record on the dawn of Bronze Age, marking the emergence of new social dynamics for the prehistoric communities in the Iberian Peninsula. It must be considered that the final window only captures part of the processes involved. In those final stages, the southern groups are strongly influenced by the cultural uniformity that radiates from the South, while the northern groups follow their own cultural trajectory, that no longer includes chert arrowheads.

This work establishes a starting point for future analyses of the cultural dynamics of peninsular Late Neolithic groups, in which the SNA will be expanded and the resolution should be increased. In order to achieve this, more detailed studies should be conducted to enhance the quality and accuracy of the radiocarbon series and the material culture attribution, Finally, as could be seen in this work the community detection algorithms hold a great potential for SNA archaeological studies. The fragmentation ratio proposed could also be employed to improve the quantification possibilities for the model of adaptative cycles, included in the Resilience Theory paradigm (Bradtmöller *et al.* 2017), providing new perspectives to this new dialectic.

Acknowledgements

I want to express my gratitude to all those who have made this work possible, especially Joan Bernabeu for his advices and insights. Also, I want to thank to the reviewers whose indications have made this work considerably better.

This work has been carried out under the framework of the research project PROMETEO 2021-007: NEONETS. A social network approach to understand evolutive dynamics of neolithic societies (c. 7600-4000 cal BP), financed by the Conselleria de Innovación, Universidades, Ciencia y Sociedades, from Generalitat Valenciana.

List of supplementary files

Supplementary file 1
“Jiménez-Puerto, J. - supplementary file 1 - Chert Arrowheads-SITES and TYPES.xls”
File with the sites, description, chronologic windows, geographic coordinates and arrowhead types present.
Supplementary file 2
“Jiménez-Puerto, J. - supplementary file 2 - Network Windows.zip”
Contains all the .csv files corresponding to the metrics of each temporal window.

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Puntas de flecha que conectan: Transmisión diferencial de la información en los albores de la Edad del Bronce

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Resumen:

El estudio de las relaciones entre las comunidades prehistóricas es uno de los principales objetivos de la arqueología actual. Una herramienta útil para enredar este tema es el análisis de redes sociales (ARS). Algunas de las ventajas que proporciona este enfoque matemático se refieren a la posibilidad de estudiar las relaciones a través de los elementos de la cultura material, o su capacidad para integrar diferentes escalas de análisis (macro-micro). Además, el ARS combinado con la aplicación de métodos estadísticos bayesianos de atribución cronológica, tiene el potencial de crear series diacrónicas de información relacional, que están conectadas con las dinámicas de los grupos sociales prehistóricos. Esta metodología permite a los arqueólogos estudiar los datos arqueológicos desde una perspectiva totalmente diferente, no sólo centrada en un punto de vista descriptivo o morfométrico y permiten una rápida exploración de los mismos. El objetivo de este trabajo es aplicar los procedimientos del ARS, junto con una herramienta bayesiana de atribución cronológica recientemente desarrollada, a yacimientos arqueológicos situados en el Este de la Península Ibérica durante el IV y III milenio cal BCE utilizando puntas de flecha de sílex como proxy arqueológico. Estos abundantes elementos arqueológicos tienen fuertes implicaciones geográficas y cronológicas en el marco escogido, en función de su morfología. Así pues, es nuestro objetivo específico analizar la transición que tiene lugar a finales del Neolítico, entre el mundo Campaniforme y la Edad del Bronce, mediante el análisis de la transmisión diferencial de la información y la variabilidad espacio-temporal presente en el registro arqueológico. Este objetivo se llevará a cabo a través del estudio de las relaciones entre los conjuntos de puntas de flecha, distribuidos por los niveles arqueológicos y se implementará confeccionando matrices relacionales a partir de la información arqueológica, que cuantifique el grado de similitud entre los diferentes contextos arqueológicos. Existen muchas formas de transformar estos datos, pero en este caso se emplearán medidas de similitud. Más concretamente el índice de Jaccard que tienen en cuenta únicamente la presencia-ausencia de los elementos, no su cantidad. Asimismo, para observar la evolución de estos flujos de información, se llevará a cabo un análisis diacrónico entre las comunidades sociales presentes en el Neolítico Final-Calcolítico-Edad del Bronce, de las que existen evidencias. Para ello, será necesario utilizar a las series radiocarbónicas existentes, que se filtrarán para tener en cuenta sólo aquellos contextos que no presenten dudas y que sirvan como base al procedimiento bayesiano de atribución cronológica. Además, con las dataciones se construirá una sucesión de ventanas cronológicas de duración fija, estructura temporal sobre la que se situarán las redes relacionales confeccionadas. Finalmente, sobre esta urdimbre se aplicarán los métodos del análisis de redes sociales con el fin de extraer una serie de métricas que permitan caracterizar las estructuras de las redes. Para concluir, se propondrá una nueva métrica que sirva para realizar una aproximación cuantitativa a la fragmentación cultural en un momento dado. Esta novedosa propuesta emplea los datos proporcionados por algoritmos de detección de comunidades para identificar grupos de sitios con comportamiento tecnológico similar, en las diversas ventanas cronológicas creadas. De este modo se pretende comprobar la hipótesis inicial que apunta a la existencia de una sucesión de pulsos de homogeneidad cultural, seguidos de otros en los que la fragmentación-regionalización es dominante.

Palabras clave: redes; puntas de flecha líticas; análisis de redes sociales; Edad del Bronce; Calcolítico