J Archaeol Method Theory
DOI 10.1007/s10816-015-9259-6

Network Analysis and Entanglement

Ian Hodder[1] **· Angus Mol**[1]

Abstract This article explores the extent to which formal network analysis can be used to study aspects of entanglement, the latter referring to the collective sets of dependencies between humans and things. The data used were derived from the Neolithic sites of Boncuklu and Çatalhöyük in central Turkey. The first part of the analysis involves using formal network methods to chart the changing interactions between humans and things at these sites through time. The values of betweenness and centrality vary through time in ways that illuminate the known transformations at the site as, for example, domestic cattle are introduced. The ego networks for houses across four time periods at the two sites are also patterned in ways that contribute to an understanding of social and economic trends. In a second set of analyses, formal network methods are applied to intersecting operational chains, or chainworks. Finally, the dependencies between humans and things are evaluated by exploring the costs and benefits of particular material choices relative to larger entanglements. In conclusion, it is argued that three types of entanglement can be represented and explored using methods taken from the network sciences. The first type concerns the large number of relations that surround any particular human or thing. The second concerns the ways in which entanglements are organized. The third type of entanglement concerns the dialectic between dependence (potential through reliance) and dependency (constraint through reliance).

Keywords Network analysis · Entanglement · Neolithic · Operational chains · Çatalhöyük

The writing of this article came about as an attempt to explore the extent to which formal network analysis could be used to study aspects of entanglement. We recognize that in archaeology at present, there is a broad family of approaches that explore networks and relationality (Knappett 2011; 2013, Watts 2013). For all these

✉ Ian Hodder
ihodder@stanford.edu

1 Stanford University, Portola Valley, CA, USA

approaches, exploratory network methods may have value. Indeed, archaeology has long used network approaches to explore relational structure as in the example of the seriation diagrams produced by Petrie based on matrix ordering.

By network analysis, we refer to methods based in graph theory that allow the study of the pattern of relationships between nodes or vertices and the links or edges or ties between them (Borgatti, *et al.* 2009; Brandes, *et al.* 2013; Scott 2000; Collar *et al.* 2015; Knappett 2011; 2013; Terrell 1977). Network analysis can be applied to a wide range of phenomena, but the specific measures most used in archaeology often derive from social network analysis, defined by Brughmans (2013, 633) as "concerned with exploring social relationships as media for the flow of resources between active individuals, corporations, or communities." The aim of a network study may be to analyze social systems, but archaeological networks are not built on the observations of interactions between people. Rather, they are built on the observations of relations between archaeologically observable phenomena: *e.g.*, patterns in material repertoires and practices, information from (zoo-)osteological records, or connections between intra-site as well as landscape features. Even if these sources of information are strengthened by a multi-disciplinary engagement with these relations—for example, through sub-disciplines that do study interactions between people, such as ethnoarchaeology—they are scaffolded by an overarching approach that is specifically geared toward the study of interdependent or entangled ties between people and things. The effect of this is that social network analyses and concepts cannot be straightforwardly adapted to archaeological cases. Still, we will argue that methods from the broader network sciences can be of use to explore these interdependencies or entanglements.

By entanglement analysis, we mean study of the ways in which the collective set of dependencies between humans and things (HT and TH), between things and other things (TT), and between humans and other humans (HH), create potentials but also entrapments that direct change down specific pathways (Hodder 2012). Although the term entanglement is used to describe a wide range of phenomena in numerous disciplines (Thomas 2009, Edensor 2011), and although the term is used in a variety of ways in archaeology (Dietler 1998; 2010, Fuller *et al.* 2010, Stahl 2002), it is used here in the sense defined by Hodder (2012) as the dialectical relationship between dependence (the reliance of humans and things on each other) and dependency (the constraints that humans and things place on each other). This definition attempts to capture the ways in which human reliance on material things draws humans into the lives, interactions, and uncertainties of things. Because things are unstable and have their own complex interdependencies, humans get caught up in things, trapped into co-dependent pathways.

In many ways, the two forms of analysis seem close. It is possible to draw "tanglegrams" that describe the dependencies of things and other things. These tanglegrams (Fig. 1) can look very like network diagrams (Hodder Fig. 9.2). "At the heart of network science is dependence, both between and within variables" (Brandes *et al.* 2013). This focus on exploring, analyzing, and modeling dependencies between entities, but also between entities, relational processes, and structures is what sets network approaches apart from other forms of data analysis.

Indeed, some aspects of entanglements seem readily to lend themselves to network analysis. An important aspect of entanglement is that any human-thing dependence is

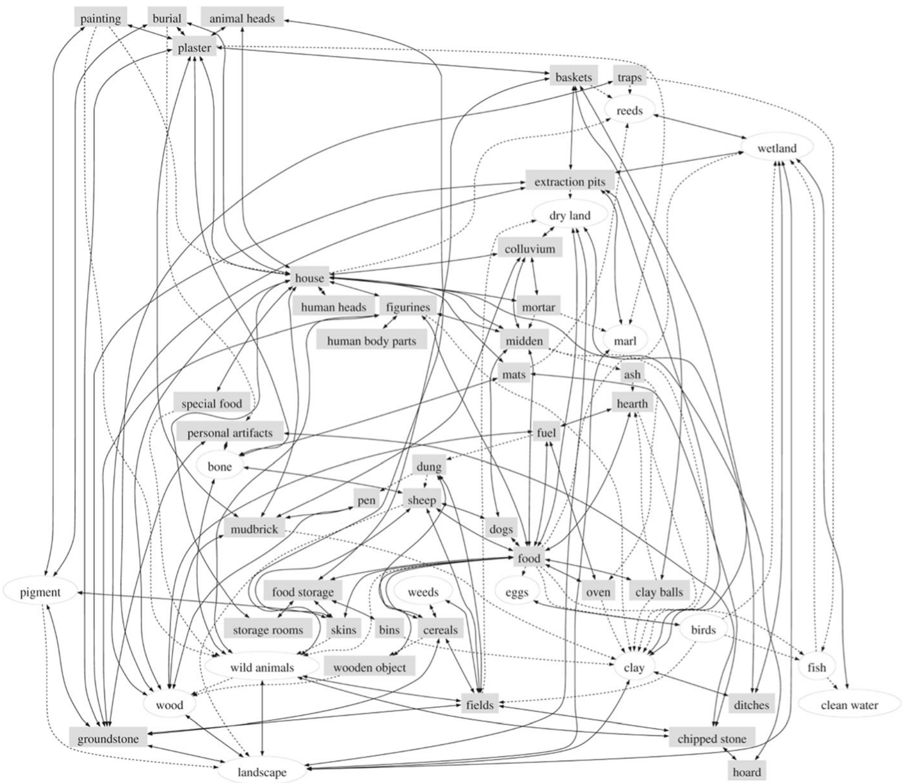


Fig. 1 Tanglegram for clay use at Çatalhöyük, adapted from Hodder 2012

tangled up in other human-thing dependencies. The human dependence on wheat in early agricultural societies was tied up with the operational sequences involved in making digging tools, threshing and winnowing implements, regenerating the soil, providing sufficient water, providing storage, and so on. Network analysis would seem useful in describing and mapping these "interactions" (Schiffer 1987), cross-craft interactions (Brysbaert 2007), or "equipmental totalities" (Heidegger 1973). Here, the constraint or "caught-up-ness" in the entanglement derives from the large number of interactions that surround any particular event or operational sequence.

Network analysis can also aid in the description and analysis of the overall structure of entanglements between humans and things. In any entanglement, there may be particular combinations of humans and things that are very central, and on which many other humans and things depend. In other cases, entanglements may be dispersed or diffuse. Similarly, in a network of nodes and links, there may be "hubs" that constrain movements and flows, as in the case of networks of flights that are routed through major airports.

Despite the apparent similarities between entanglements and networks, we started with a suspicion that the two forms of analysis had incompatible components. Although any quantification of social interactions involves a degree of reductionism, entanglement is concerned with exploring the full complexities of real-world practices. If it was possible to fully disentangle entanglements, they would no longer be entangled. But, as

Brughmans (2013, 641) emphasizes, "neither SNA nor complex networks techniques are designed to unravel the full complexity of social interactions, and archaeologists should definitely not apply them as if they were" (a similar point is made by Pachucki and Breiger 2010 in relation to the sociology of cultural relations). Individual disciplines within the network sciences target different phenomena, and abstract and substantivize them in different ways. Our intention is neither to set up an entanglement approach in opposition to the vast inter-disciplinary field of the network sciences, nor to determine if and where entanglement studies fit within them. Network studies can be connected to entanglement through the focus on network analysis. Network analysis provides "a formal mechanism for representation, measurement, and modeling of relational structures" (Butts 2009, 414). Here, we will discuss how entanglement as a phenomenon can benefit from, or potentially be challenging for, a network analytical approach.

While network analysis focuses on the overall form of dyadic links between multiple nodes, entanglement is primarily concerned with the substantive nature of those links. In particular, the focus on the dialectical relationship between dependence and dependency implies that the links between nodes may be difficult to summarize in network terms. For example, a dependency relationship between humans and emmer wheat at the dawn of agriculture led to genetic change in the wheat such that, as a result of a tough non-shattering rachis, wheat could no longer reproduce itself without human intervention. Humans and wheat thus became co-dependent or co-reliant. But as a result, humans were also drawn into harder labor in order to thresh and winnow (Fuller *et al.* 2010). The relationship involved dependency in that humans became both enabled by and constrained by wheat, trapped into pathways involving new forms of labor and new technologies. It would seem difficult to encapsulate such complex relationships between humans and things in a network analysis, although we will explore this issue further below. While there has been much study of the diffusion of innovation, including agricultural technologies, using network approaches (e.g., Rogers 2010), the entanglement perspective focuses more on the long-term dependencies and entrapments that are created.

Another potential problem in applying network analysis to entanglements is whether paths in networks are the same as operational sequences in entanglements. Operational sequences of humans and things seem to be mimicked by the notion of paths in network analysis, but there is a difference. In much network analysis in archaeology, the focus is on geodesic paths, *i.e.*, the shortest path between nodes, and on how many ties or degrees separate A from B. Any point in the network can be the origin and any point the destination. But in an entanglement of operational sequences, the nodes are arranged in a particular sequence related to the temporal processes of production and consumption. The narrative networks described by Pentland and Feldman (2007) are temporally sequential, as are citation networks and disease networks. Operational chains have an upstream (the sourcing of materials and their manufacture into tools) and a downstream (use, repair, and discard). We will need to explore whether network analyses can be adapted to such aspects of entanglements in archaeology.

There are some general problems we have encountered in using network approaches to study entanglement, though these problems are not specific to the entanglement case. One is the problem of defining nodes. This is a widely found problem. For example, in plant biology is a feeding site the leaf, the bark, or the whole tree (Butts 2009, 414)? In social analyses, is a node or actor one individual or a group of individuals? In the archaeological case, is the "house" a node or should one delve down to smaller entities such as the walls of the house? How the entity is defined will affect the analysis. As in any analysis, node definition depends on the questions that one is asking and whether an entity can be reliably and consistently identified, as well as on the relationships between nodes ascertained. In addition, in the case of both entanglement and network analysis, there may be a problem in the non-equivalent status of nodes. For example, it is entirely possible for an entanglement to consist of human individuals, animals, an action, an element of the landscape, and material things.

There is a lingering perception that defining the boundaries of a network is problematic (Strathern 1996). This is based on the incorrect assumption that networks need to correspond to some form of natural groups. Instead, they are bounded based on the questions one means to answer with a network (Borgatti and Halgin 2011). Archaeological networks are thus necessarily unbounded and multi-scalar entities, being contingent on a set of questions as well temporal and spatial scales (Collar *et al.* 2015). In the specific case of entanglements, in which things depend on other things that depend on other things in endless sequences that often have no obvious bounds, we have attempted to follow the general guideline by Butts (2009, 414) that "the set of nodes should be defined so as to include all distinct entities that are capable of participating in the relationship under study." In other words, entanglements explored or analyzed as a network are always a specific set of entanglements, coalescing around a particular set of people and thing dependencies. As a result, an additional approach to the boundary problem has been to focus on specific ego networks. An ego network consists of a node (ego), its first-order ties or neighbors (alters), and all the ties between alters. Looking at first-order neighborhoods is attractive, because it somewhat diminishes the problem of the fragmentary nature of archaeological relational data (Mol *et al.* 2015). Instead of trying to complete and explain the absences in whole networks, ego networks focus on the dependencies in much smaller networks. Everett and Borgatti (2005) have shown that there is a relationship between the betweenness (see below) of overall networks and ego betweenness.

In this paper, we explore aspects of the data from the 7100 BC–6000 BC site of Çatalhöyük East in central Turkey (Hodder 1996, 2000, 2005a, b, 2006a, b, 2007, 2013a, b, 2014a, b, c) and from the earlier site of Boncuklu 9 km to the north (Baird 2007a). Both sites are in the Konya region of the central Anatolian Plateau and are part of a sequence that continues from the Epi-Palaeolithic (at Pınarbaşı—Baird 2007b) through the Aceramic Neolithic (at Boncuklu and Çatalhöyük) to the Ceramic Neolithic (at Çatalhöyük). Boncuklu, dated to the later 9th and early 8th millennia BC, is a small 1 ha site with scattered oval houses and an economy based on wetland resources, some incipient domestication, and a range of wild resources. Much of the following analysis is based on the evidence from Çatalhöyük which is a 13 ha site of densely packed housing and, by the end of its occupation, a full suite of domesticated plants and animals. The site was originally excavated in the 1960s by James Mellaart (1967), and more recent work has concentrated on renewed excavations in the North and South Areas. The original sequence of occupation identified by Mellaart has more recently been changed to take into account new stratigraphic evidence (Farid 2014) and the main South sequence now runs from South G at the base to South T, with TP levels above. For the purposes of this paper the sequence has been grouped into phase 1

(South G to O), phase 2 (South P to T), phase 3 (TP). In parts of the analysis we have further subdivided phase 1 into 1A and 1B (see below). Our aim in this paper is to use the Çatalhöyük and Boncuklu data in order to see whether and to what extent network analyses can contribute to the study of entanglement as defined above.

Entanglement Networks

Our point of departure was to transform the tanglegram published (Hodder 2012) as Fig. 9.2 (reproduced here as Fig. 1) into a formal network (Fig. 2). The original tanglegram (Fig. 1) attempted to diagram all the relationships between things associated with clay and plaster in the lower levels of occupation at Çatalhöyük (phase 1). More specifically it attempted, in the terms identified by Butts above, to include all things that are capable of participating in the uses of clay at the site. An asymmetric matrix of dependencies, *i.e.*, a directed network, was produced. The reason for this was that some dependencies are not reciprocated: A depends on B (thus mudbrick depends on clay) but B does not depend on A (in this case the existence of clay in the landscape does not depend on mudbricks). One unexpected outcome of the process was that the step-by-step construction of the relational matrix was itself of value. The format of the matrix forced the analyst to consider all possible dyadic relations, several of which had been missed or not thought through in the drawing of the original diagram. Visone (Brandes and Wagner 2004), the network analytic software that was used to plot the new graph, also has several algorithms for the automated laying out of networks. This yielded a better visualization (Fig. 2) of the information contained in the relational data than was the case in the original figure.

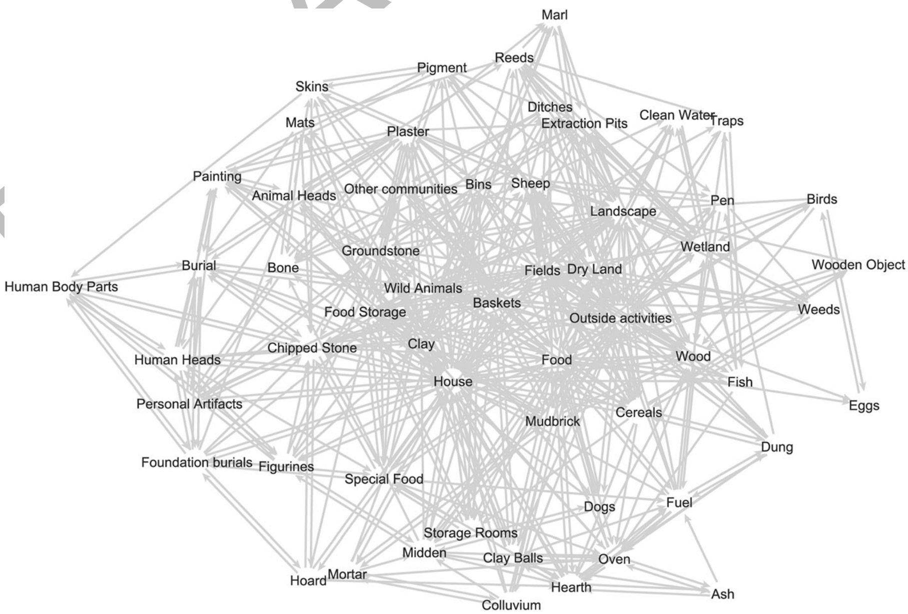


Fig. 2 Formal network for clay use at Çatalhöyük

The process of discerning links between nodes in an entanglement has been described (Hodder 2012, 181–2). Each link is based on evidence, or more properly on the interpretation of evidence. Thus mudbrick depends on clay because analysis of the fabric of the mudbrick shows that clay was involved in their manufacture, and we have sourced the types of clay used at different time periods (Doherty 2013, Love 2013, Tung 2013). But clay does not depend on mudbrick because even with extensive use of clay to make mudbrick there remained large available resources in the landscape—thus the presence of clay in the landscape is only marginally affected by use for mudbrick, so clay does not depend on mudbrick. Midden too depends on clay in the sense that clay or marl was spread over middens, either to clean or to level them or as a result of other clay-based activities (an interpretation based on the micromorphological work of Matthews 2005 and Shillito *et al.* 2011), but again clay does not depend on midden. Houses depend on middens (since houses were carefully swept clean and the middens contain small lenses of material that are interpreted as likely coming from houses), and middens depend on houses (for the refuse that constitutes them). Drawing up the tanglegrams is thus based on detailed contextual knowledge about activities on a site and the large volume of research that has been conducted there.

The tanglegrams initially discussed here all describe thing-thing relationships. There has not been an attempt at this stage to model separately human and social dimensions, that is human dependence on things, thing dependence on humans, and human dependence on humans. The exploration of the entanglements at Çatalhöyük and Boncuklu targets the degree and betweenness centralities of nodes. Degree centrality is measured by counting all the incoming and outgoing ties of nodes which, when averaged across the degree centralities in all individual nodes, allows for an identification of those nodes that are involved in most entanglements. Betweenness centrality is a member of a family of geodesic path-based centralities (Borgatti et al 2009). This means that a node's betweenness centrality in the thing-thing tanglegram is measured by determining the shortest paths between a pair of nodes in a network and calculating which fraction of the paths run through the node in question, repeating this measure for all pairs of nodes in the graph and summing up all of these fractions. Even if such a node does not have the highest number of ties it may have a position that is structurally important, which is in line with the emphasis on pathways (Hodder 2012: p. 105).

The network analyses provided measures that described the tanglegrams in ways that allow comparison. It was decided to conduct network analyses of equivalent tanglegrams for other phases at Çatalhöyük (phases 2 and 3) and at the earlier site of Boncuklu (Baird 2007a). The overall period of time from the early 8th millennium BC to the late 7th millennium BC sees the introduction of pottery and domestic cattle, and there are many changes in the overall organization of society, economy, and culture. As a result, the nodes in the tanglegrams for each time period differ, and this has to be born in mind when evaluating the results.

It is of interest that across all four time periods, house and food remain the highest ranked nodes in terms of betweenness (Fig. 3) and centrality. This very much aligns with current interpretation of the two sites Boncuklu and Çatalhöyük. The latter site in particular has been interpreted as an example of a house society and individual houses have been termed "history houses" because they seem to be the foci for handing down ritual objects of importance while at the same time being the houses of burial (Hodder and Pels 2010). Houses at Çatalhöyük are used for burial, food preparation and

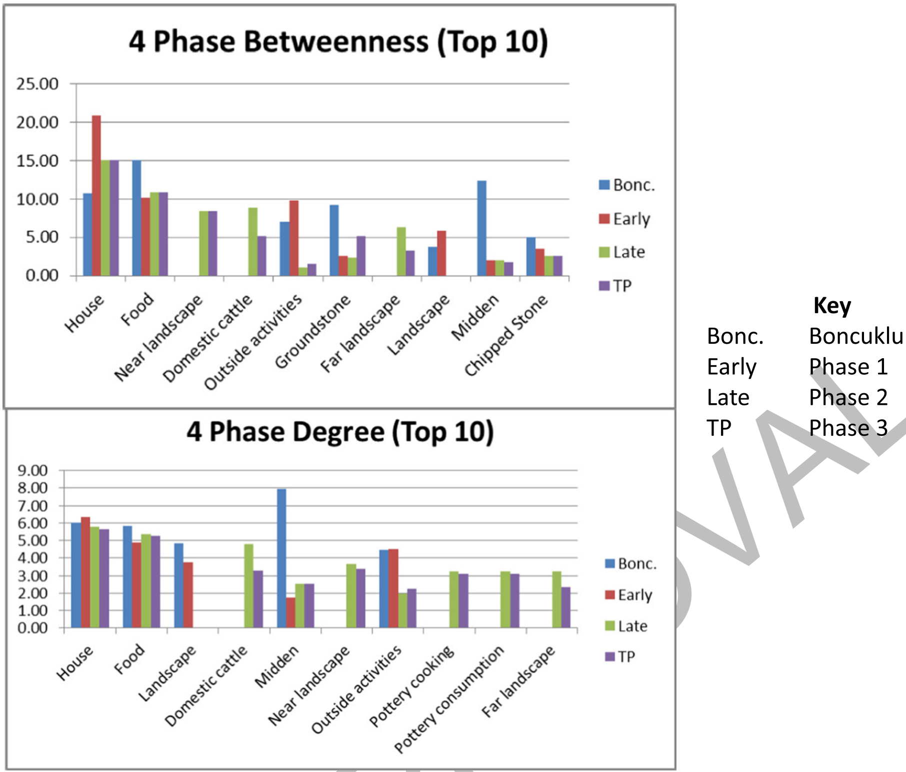


Fig. 3 Top 10 four phase betweenness and degree

consumption, ritual, artifact production. Indeed it has been argued that at this time "everything is brought into the house" (Hodder 2006b), and there is much evidence for a house-based scale of economic production (Hodder 2014c). Clay use too was often organized at a house level, with some evidence of separate houses using their own mudbrick recipes. There is no evidence of public buildings, chiefly centers, or religious elites; many aspects of life were organized through the house. This was largely a domestic mode of production although larger sodalities and groupings existed (During 2006, Marciniak and Czerniak 2007, Mills 2014).

Equally, food was a central focus in the domestic realm. Many of the activities in the house involved the use of clay to make ovens and hearths, and cooking initially in phase 1 involved the use of clay balls heated in the oven (Atalay 2005). Clay was used in food storage bins and domestic and wild animals were involved in different scales of consumption and group feasting, mostly house-based (Demirergi *et al.* 2014). Cereals were stored still husked and were processed at the house level by pounding and grinding using querns (Bogaard *et al.* 2013).

It might be objected that houses and the food in them appear as central because we only dig houses at Çatalhöyük. It is true that at this site, as already noted, a domestic mode of production and a lack of public buildings reinforce the notion of a house-based society, which the network analysis picks up well. But there are also middens and open areas at Çatalhöyük and these could have come to the fore in the analysis. Indeed there is an important shift through time. There is markedly less going on in the Boncuklu houses in comparison to Çatalhöyük. The Boncuklu houses are smaller, there are not room divisions and there is little evidence of storage facilities. More activities take place on the outside middens than at early Çatalhöyük. This latter point is expressed very clearly in the changing betweenness of midden through time. At Boncuklu the value for midden is 12.37, but the value drops to around 2.00 in the three phases at Çatalhöyük. The settlement pattern at Boncuklu is much more open; houses are not tightly packed against each other as is found in the classic agglomerated neighborhood structure at Çatalhöyük. There is more space for activities in open areas at Boncuklu and the social system seems less house-based. At Boncuklu food is ranked higher than the house in comparison to Çatalhöyük in terms of betweenness (Fig. 3). These shifts express very well our current understanding in the sense that in the Neolithic of the Middle East and Anatolia there is good evidence that houses gradually increased in size and internal functions. Throughout the region, more and more was brought into the house during the Aceramic Neolithic (Byrd 1994, Kuijt and Goring-Morris 2002).

Phase 1 at Çatalhöyük includes the classic levels of Mellaart's VII-VI and the current team's South M-O. This is the time period when the house is at its most elaborate, with most evidence of burial, and most plastered installations of bull crania and other animal parts. It is the period when most reliefs are found on the walls of houses. In the later levels at the site, the house remains important but there is more separation of houses from each other, and more use of adjacent open areas and yards. Doorways into open areas appear. The changes are well expressed in the high betweenness in phase 1 for the house (20.83) and the lower values in the later levels (15.06 and 15.08 in phases 2 and 3).

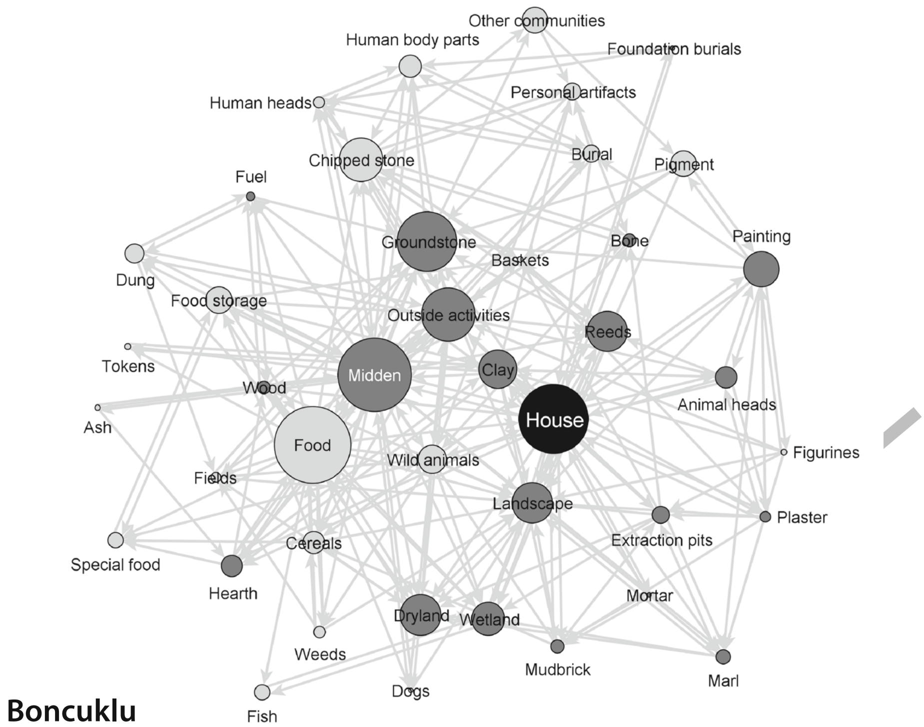
Other shifts in the betweenness values are equally informative. In comparison to the early role of wild animals, domestic cattle, introduced by phase 2 at Çatalhöyük, immediately have a greater impact. Domestic cattle come in immediately at a high value. We know that the introduction of domestic cattle had considerable impact, being used for a wide range of functions including milk consumption and taking a role in special feasting and deposition (Pitter *et al.* 2013, Russell *et al.* 2013). Wild bulls are less frequently found in installations in the upper levels. There is also evidence for more focus on individual personhood in the upper levels, with more evidence of personal ornamentation and more evidence of long-distance materials being used in bead production (Vasić *et al.* 2014). The increase in the betweenness values of personal artifacts (0.78 and 0.37 in Boncuklu and phase 1, and 4.66 and 3.49 in phases 2 and 3; not shown in Fig. 3) expresses this shift.

It is not surprising that the results of these representations correlate so well with existing knowledge since it is that knowledge that led to the construction of nodes and links in the matrices of dyadic relations. Thus at one level the resulting tables and graphs simply reproduce existing knowledge. On the other hand, they allow a transparent and visual representation that promotes comparison and discussion. They allow the rate of change between periods to be explored and related to wider theories. The network exploration is thus a useful component in an interpretive procedure. It contributes to debate, clarifies arguments, and leads to new inquiry. For example, why do the betweenness values for midden decrease after Boncuklu while those for outside activities do not decrease until after the early phase at Çatalhöyük? While this dichotomy had not been noticed in earlier discussions, the network analysis draws out a clear pattern. In the early phase at Çatalhöyük the range of activities in midden areas is greatly reduced in comparison to Boncuklu, but outside areas are used for a range of non-midden activities such as animal pens or lime plaster firing, and areas near the site are used for fishing and the collecting of eggs. The network analysis has helped to identify a change in the use of space through time.

As already noted, overall betweenness centrality values depend on the overall density of the network (the percentage of ties that are present relative to the amount of ties that would be present if every node was maximally connected), particularly in relatively small networks. In addition, it remains difficult to compare networks when they do not consist of the same nodes and the same amount of nodes. Yet in these models the type and number of nodes necessarily change as cooking pottery and domestic cattle are introduced. An alternative approach is thus to focus on ego networks. An ego network aims to abstract, model, and analyze the direct network around one node, referred to as ego. Also known as centered graphs, they were pioneered by the sociologist Linton Freeman (1982) and were developed with an eye to better understand the position of individual actors within larger social structures. Instead of focusing on the structural properties of social networks as a whole, ego networks can be used to understand the effects wider networks have on a particular individual (Mol *et al.* 2015).

Figure 4 shows the ego networks for house across the 4 time periods. In this case the ego network consists of a node (ego), its first- and second-order ties or neighbors (alters), and all the ties between alters. The size of nodes in the diagrams is based on betweenness centrality. The color of the nodes is: black (ego), 1 distance (dark gray) and 2 distance (light gray). The networks show nicely the greater centrality of the house after Boncuklu as well as the greater importance of midden at the earlier site. Comparison of the four networks also shows the greater betweenness centrality of the house in phases 1 and 3 at Çatalhöyük. This visual impression is supported by a series of measures of the four networks, as shown in Fig. 5. The overall network density percentage, and the absolute value of house betweenness show peaks in phases 1 and 3 at Çatalhöyük.

These results fit very well with our understanding of the changing role of the house at the site (Hodder 2014b). Phase 1 includes the high point of "classic" Çatalhöyük, made famous by the excavations of James Mellaart in the 1960s. At this time, population densities are at their highest, there is high reproductive fertility, much burial within houses, and a great elaboration of ritual and artistic expression. Bucrania and other animal installations are common in houses. After phase 1 there is a major change in the sequence at Çatalhöyük, and increasingly in the upper levels there is a greater focus on the independence of house units and their productive capacities. By phase 3, in the final centuries of occupation on the East Mound, the house has become very large, with very thick walls, large central rooms with central hearths, and a greater focus on mobiliary art and pottery rather than wall art; burial occurs in tombs rather than in houses (Marciniak and Czerniak 2007). By phase 3 the house has taken on a new centrality based less on rituals associated with the dead, plastered animal heads and long-term ancestry, and more on production and social exchange, for example through the use of more elaborate pottery used for social consumption. Comparison of the ego networks for phases 1 and 3 shows these differences clearly. The ego network for the house in phase 1 shows the house strongly linked to clay (including for plastering animal skulls) and wild animals, as well as linked to burial, human head circulation and foundation burials. In phase 3, on the other hand, the house has strong links to domestic cattle, fields, and pottery consumption, although food is still involved in special deposits, and the near landscape is intensively exploited. There are no first- or second-order links to burial. The analysis of ego networks picks up details of the changes through time in the role of the house that were not picked



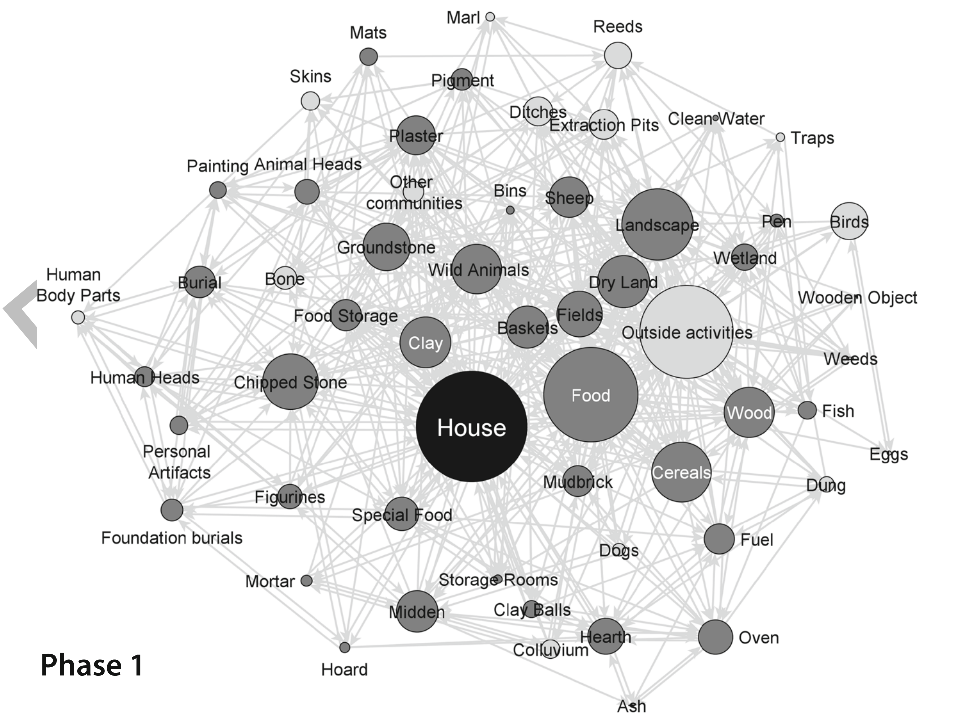


Fig. 4 Ego networks for house across the four time periods

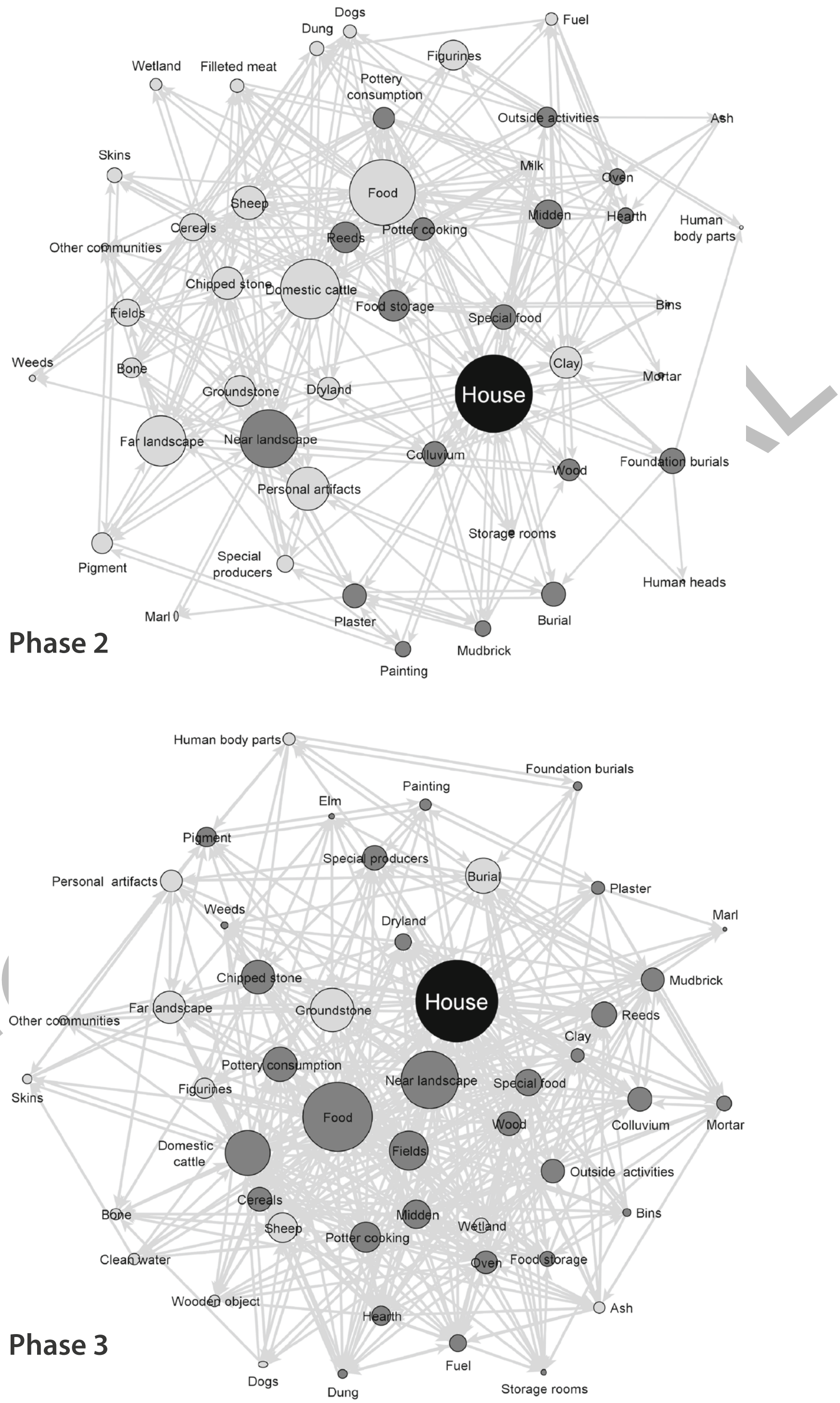


Fig. 4 (continued)

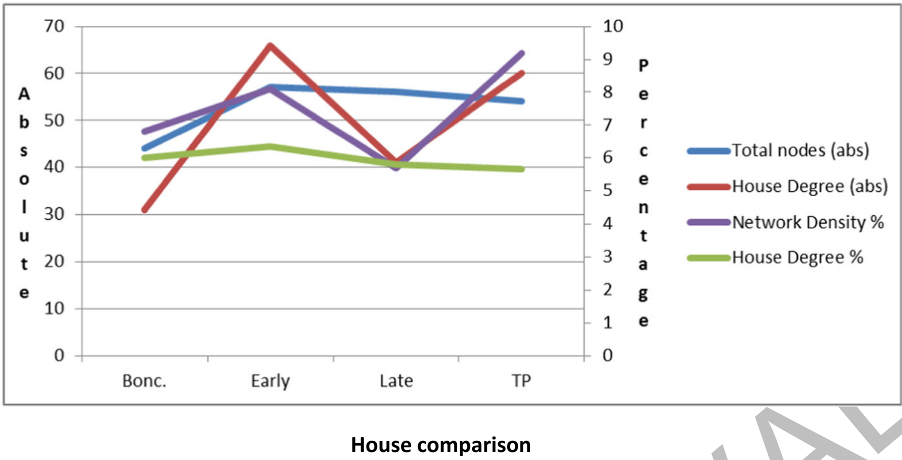


Fig. 5 Comparison of the four ego networks for house

up in the earlier analysis of the overall entanglements (Figs 2 and 3). The results of the two types of analysis are similar, but the focus on one node and the first- and second-order links of that node allow a more careful consideration of the role of the house through time. In particular, the shift in the nature of the house centrality between phases 1 and 3 becomes clear.

From Networks to Chainworks

However, the focus on first- or second-order links can in other respects be seen as a disadvantage. In practice, archaeologists know that nodes in operational sequences are arranged in long sequences from procurement to discard often described as behavioral chains or *chaînes opératoires* (Schiffer 1987, Leroi-Gourhan 1943, Lemonnier 1993). While these two types of operational chain are usually described as unilinear sequences from procurement to discard, it is widely recognized that they may loop back on themselves, as when a clay mudbrick is broken down and used to make new bricks. A more complex picture is built by pointing to the other artifacts used at any stage along a chain. For example, in the manufacture of an obsidian blade, a bone or antler point may be used that has its own sequence from procurement to manufacture to use (to make the obsidian blade) to discard. Thus all operational chains are threads in numerous cross-cutting chains. These different chains have to "wait for" each other—they have to be organized temporally in relation to each other. The making of the obsidian blade depends on the pre-production of the bone or antler point. One of the oft-cited criticisms of Actor Network Theory (Latour 2005) is that it pays insufficient attention to temporality. We wished to explore whether the description of paths in network analysis (Brughmans 2010, Knappett 2013) might allow an understanding of the directed ties or processes that engender pathways or "operational chains." A key component of entanglement is that individual humans and things are caught up in multiple threads or chains of intersecting sequences (Hodder 2012). Can network analysis capture some of this "chainwork"?

One advantage of approaching networks and entanglements in terms of operational chains is that the latter provide some degree of solution to the problem of how to determine boundaries. Earlier, we stated that the boundaries of networks of entanglement could best be identified in terms of functional inter-dependence, but in practice it is often difficult to determine where such inter-dependence might cease. It remains difficult to discern what node to include and what to exclude. The use of ego networks constrains the search, but on arbitrary grounds (in the above case to second-order links). The following of operational chains allows a less arbitrary and more secure identification of what is relevant to the network and what is not. Operational chains start with upstream activities (procurement and manufacture) and end with downstream (use and discard) and although looping and intersections occur, this rule of thumb provides some constraint on the choice of relevant nodes.

Another advantage of approaches to entanglement that focus on operational chains is that the nodes are actions rather than things or humans. In the networks described above, the nodes have been things and the links the dependencies between things. The advantage of such a formulation is that it draws stark attention to the way that humans get caught in the entanglements of things and their inter-dependence, but the disadvantage is that humans are not directly involved as co-producers of entanglements (Ingold 2000; 2010). By focusing on human-thing actions in operational sequences (humans making pots, humans discarding refuse), the artificial separation of humans and things is avoided, and the wider links between networks and theories of practice and agency can be explored (Knappett 2011) . Pentland and Feldman (2007) describe forms of network analysis that explore how humans use tools to do tasks in complex re-combinable sequences. Their notion of narrative networks in which the pathways in operational sequences are defined, is built upon Actor Network Theory, structuration theory and theories of organizational routines.

An example is provided here of the application of network path analysis to entanglements of operational chains. In early phase 1 at Çatalhöyük, cooking was achieved by firing clay balls that were then reheated and placed with food in containers such as baskets (Atalay 2005). In later phase 1 and in phase 2, cooking was increasingly carried out using clay pots (Last 2005, Yalman *et al.* 2013), and residue analyses of lipids in cooking pots demonstrate a preponderance of ruminant adipose fats (Pitter *et al.* 2013). Why did the inhabitants at Çatalhöyük switch from cooking with clay balls to cooking in pottery? In her experimental and ethnographic research, Atalay (2005) showed that while cooking with clay balls was very efficient, it demanded more time from the cook as balls had to be frequently reheated and changed over. The cooking pot, on the other hand, could be set on the hearth and allowed to cook—the pot acted as a delegate for the cook (Latour 2005).

But what about all the other operational chains involved in these cooking processes? Was early pottery used for cooking because it involved fewer cross-cutting chains? In order to explore this question, we described the operational chains for cooking with clay balls, as well as their cross-connections (Fig. 6). We did the same for cooking pottery (Fig. 7). We then diagrammed the same information as paths within a network analysis (Figs. 8 and 9) where each path is an operational sequence. It is particularly clear in the latter cases that operational chains overlap and intersect. For example, in the clay ball network diagram (Figs. 6 and 8), obtaining obsidian and knapping it is part of the paths to both process meat and to cut reeds. In addition, the paths are sometimes circular. For example, knapping obsidian to process a carcass produces bone from which tools are made to knap obsidian. So the paths are complex and it was not as easy

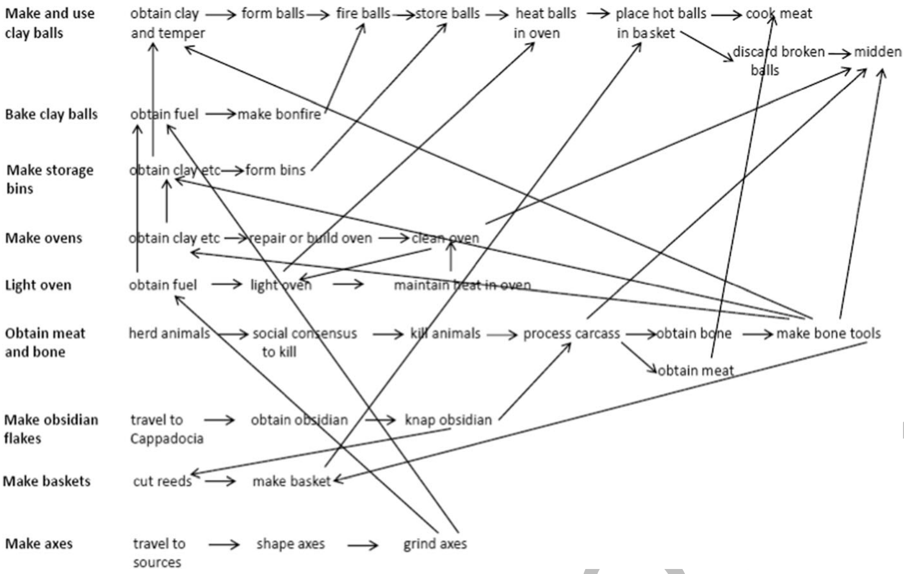


Fig. 6 Operational chains for cooking with clay balls and their cross-connections

to define their beginnings and endings as had been hoped. The overall connectivity of the clay ball network (Fig. 8) gives a Density of 0.048, and an Average Degree of 1.400. For pottery (Fig. 9) the figures are 0.053 and 1.280. As a result of the issues identified above we found it difficult to interpret these values.

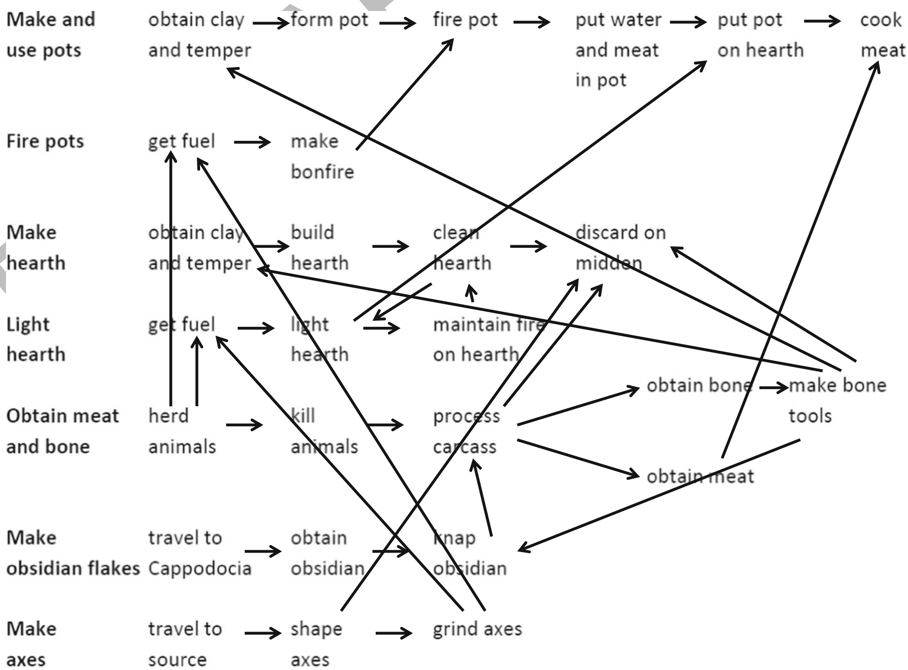


Fig. 7 Operational chains for cooking pottery and their cross-connections

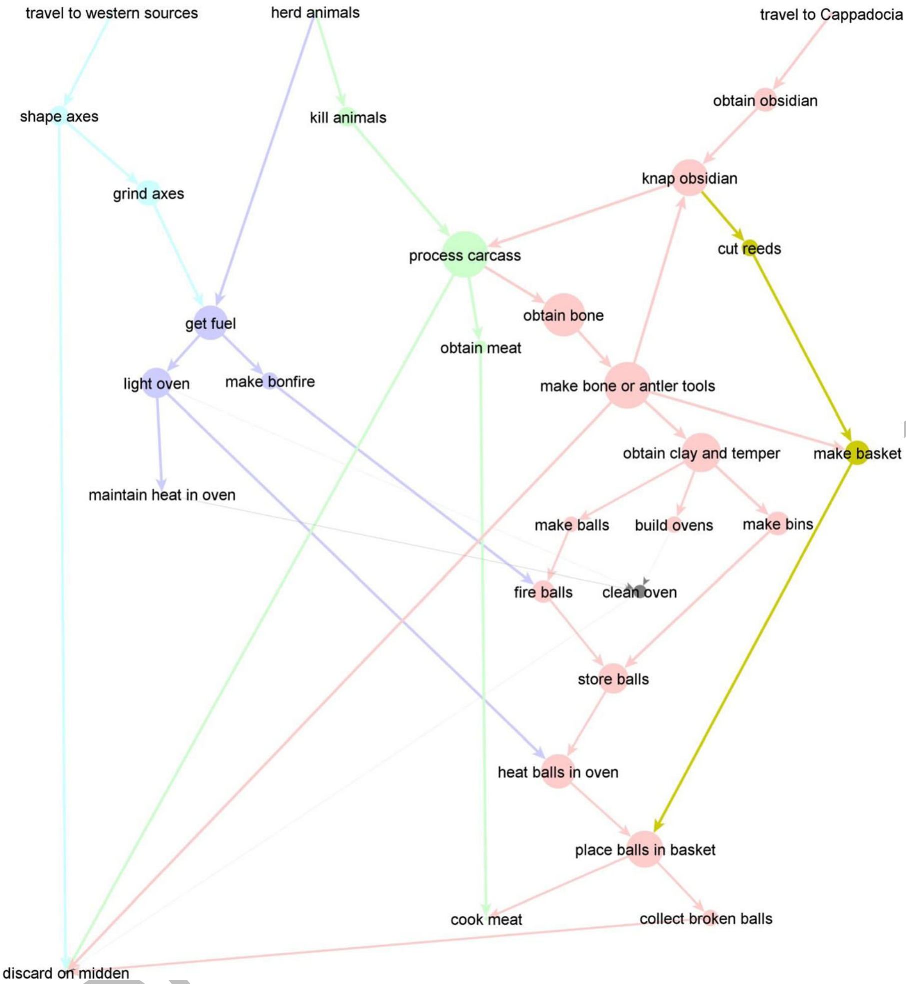


Fig. 8 Diagram for cooking with clay balls as paths within a network analysis

The main result of the transforming of operational chains into paths in networks is that some temporal confusion is caused, because the network method tries to find as few short paths as possible. For example, the clay balls network suggests that in order to cook meat one kills an animal, then processes the carcass to obtain meat. But in the diagram one cannot cook the meat until the bone from the carcass has been obtained, so that tools can be made in order to dig for clay, so that clay balls can be made, so that they can be heated in the oven—finally allowing one to cook meat! In fact, however, the making of the clay balls would usually have happened prior to obtaining meat to cook. As another example, the network diagram for cooking with clay balls makes it seem as if every lighting of the oven involves travel to the source of ground stone in order to shape and then grind axes so that wood can be obtained for use as fuel in the lighting of the oven. In fact, however, the ground stone axes could be used multiple times and fuel could be stored for multiple oven lightings.

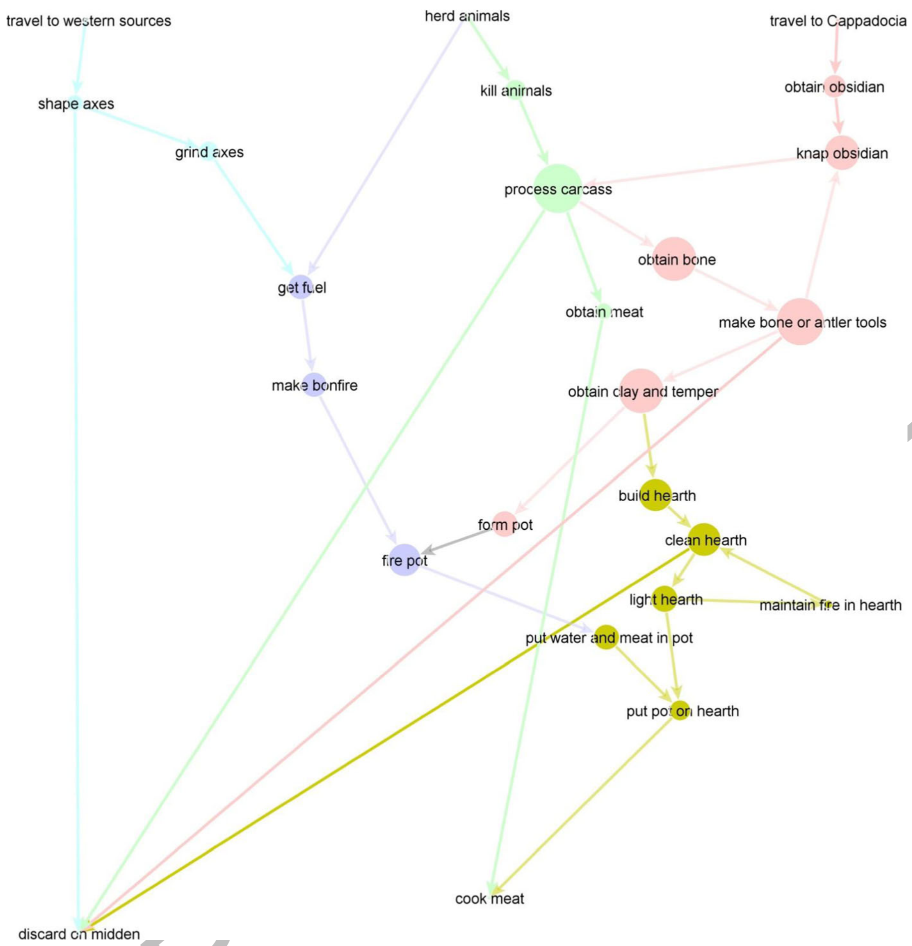


Fig. 9 Diagram for cooking pottery as paths within a network analysis

So, in this case, the enumeration of separate operational chains, where each chain is defined as having upstream to downstream components—that is from sourcing to use and discard—proved more productive (as in Figs. 6 and 7). This approach allows the chains to be better controlled (each defined in terms of upstream to downstream), and it allows sequences to run in parallel, thus retaining a fuller sense of the temporalities involved.

The descriptions provided in Figs. 6 and 7 allow the following comparisons to be made of the entanglements of cooking meat with clay balls in comparison with cooking meat in pots.

	Clay balls	Pottery
Number of chains	9	7
Average number of links per chain	2.4	2.7
Number of cross links between chains	21	16
Average number of cross links per chain	2.3	2.3

In this example, it is evident that cooking with pottery is less entangled than cooking with clay balls, in the sense that fewer operational chains are involved, with fewer cross links between them (compare Crown and Wills 1995). In other instances one might find that the average numbers of links per chain (the lengths and interconnections between chains) might show major change, which is not the case here. Cooking with pottery does not necessitate the manufacture of other containers (baskets or wooden bowls) that were needed in the case of cooking with clay balls, and it does not necessitate making storage bins specifically for storing clay balls. Pottery was rarely discarded in contrast to the clay balls that frequently cracked and broke as they were heated, cooled, and reheated. The initial adoption of cooking pottery thus makes sense not only in terms of saving time and energy (as determined by Atalay 2005) but also in terms of the overall entanglements of using pottery. In addition, we have assumed in the pottery cooking scenario that the pots were locally made but there is evidence that some of the pots were obtained by exchange (Doherty and Tarkan 2013); this again would decrease the number of operational chains for pottery cooking even if exchange links are included.

An additional way of exploring the wider entanglements that are brought into play in a particular operational sequence is to link the chainwork analysis described above with the earlier study of betweenness in wider entanglements. This allows us to explore different scales of entanglement. A local entanglement in which only a few variables are considered may look very different if other cross-cutting chains are considered. We have already seen one example of this: the adoption of cooking pots results in baskets not being necessary for cooking, but baskets may still have to be made if they are used for non-cooking functions. Thus the fact that the baskets are not used for cooking may not be an overall saving. More generally, the objects used in an operational chain may be tied up in other operational chains not considered in a small-scale analysis. For example, we can consider the main sets of objects used in cooking sheep meat in phases 1 and 2 at Çatalhöyük. As already noted, the lipids found in cooking pottery at Çatalhöyük indicate the cooking of ruminant adipose fats rather than milk, and it seems very likely that the pots were mainly used for processing domesticated sheep products given the very high predominance of sheep bones in the faunal assemblage (Russell *et al.* 2013) and given that the pots are too small to hold very much cattle bone. If we only consider comparable objects (e.g., hearth or oven, clay balls or pottery), used in cooking sheep meat in phases 1 and 2, the following betweenness centrality values are obtained from the analyses of overall entanglements described above (e.g., Fig. 2).

Phase 1	Clay	Balls	Sheep	Oven	Chipped stone	Fuel	**Total**
	2.93	0.33	1.84	1.35	3.53	1.03	11.01
Phase 2	Clay	Pottery	Sheep	Hearth	Chipped stone	Fuel	**Total**
	0.52	1.27	2.79	0.63	2.57	0.38	10.16

Here, we see that the overall betweenness centrality values associated with cooking meat in the house decline slightly, perhaps contributing to the attractiveness of switching from clay balls to pottery. But we also see that pottery itself is rather more nodal in relationship to the entanglements as a whole than are clay balls. This is because pottery affords a wider range of functions than clay balls, and this higher nodal functionality may have been an attraction.

It should also be noted that while the analysis of chainworks rather more satisfactorily captures the involvement of humans and things with each other within entanglements, it is still the case that the sequences described here are very material-centered. The operations do not take into account social and ritual components and there are no social and ritual events in the sequences. For example, the killing of an animal to obtain meat would have been preceded by a social decision to go hunting or to take an animal from the domestic herd. We have no reason to think that cooking with clay balls and pottery involved different amounts or scales of social and ritual involvement at Çatalhöyük and it is for this reason that they have been excluded here. Nevertheless, the involvement of social dimensions needs to be considered and included where possible, as will be shown below.

Relational Costs and Benefits

The network and chainwork approaches described above evaluate a link or edge between nodes simply in terms of presence or absence. They focus on the overall structure of the network. They thus allow exploration and representation of entanglement that comes about through the overall structure. One part of a chain, or a dyadic pair, is seen as entangled if its nodes are very central in relation to the whole chain or in relation to the network as a whole. Thus in the chainwork example used above, cooking pottery was introduced at least partly because it meant that cooking meat was less entangled in relation to all the component parts and practices.

But this type of analysis is not allowing representation and exploration of the nature of the dyadic ties themselves, the ways in which dependence and dependency interrelate in any specific process. For this we need to develop quantitative analysis of the ways in which things and humans afford and constrain each other. One approach would be to work out the costs and benefits of individual things or practices in relation to the wider entanglement. Human Behavioral Ecologists have attempted to develop mathematical analysis of technological investments among hunter-gatherers and have included variables such as manufacturing time to make a particular technology, procurement or return rates of using that technology, foraging time, "utility" in terms of calories (Bettinger *et al.* 2006, Ugan *et al.* 2003)

In such approaches, costs and benefits are often assessed in terms of universal optimization or maximization criteria. Winterhalder (1983) does evaluate foraging costs and benefits relative to the time and energy required for other activities, but a limited set of variables are included. In the entanglement approach, costs and benefits can only be seen as relative to the entanglement as a whole. For example, the costs and benefits of cooking pots of a particular type or fabric cannot be assessed universally, in terms of optimizing heat transfer or maximizing liquid retention. Rather, the costs and benefits are assessed in terms of specific cooking pots (of a particular size *etc.*) in relation to a specific function, such as cooking sheep bones. Cooking sheep bones in small pots differs from cooking cattle bones as the latter are larger and the overall carcass is bigger, so using small pots is less efficient if the aim is to cook the whole carcass. So the costs, benefits, and efficiency of a cooking pot are relational as in the performance matrices described by Schiffer (2004). How effective they are at cooking also depends on cooking method, for example suspended over a hearth or placed on or in an oven. In addition, it is important to evaluate the social dimensions of technologies. For example, the costs and benefits of cooking sheep with pots are also affected by the social values given to cooking, pots, and sheep. The study presented here as an example explores again the introduction of pottery at Çatalhöyük, but extends to the introduction of domestic cattle. In this case, the stratigraphic sequence has been divided so as to allow more detailed discrimination between the levels of occupation in which pottery is introduced. As noted above, cooking pottery was introduced in the later part of Phase 1. Phase 1 has therefore been divided into A and B subphases.

Phase 1A: Lowest levels: South G-L in which cattle were wild and cooking was carried out with clay balls as described above. There was heavy processing of domestic sheep carcasses in the house to produce meat that was cooked on the bone, and to obtain marrow, fat, and grease. Clay balls were heated in the oven and then placed in baskets. Most wild cattle meat was processed outside the house and often in relation to larger social groups than the house. Bulls were preferred in feasting and bull horns were often placed around burial platforms in houses. Use wear analysis (Lemorini and D'Errico 2014) suggests that obsidian flakes were used for a wide range of functions including the processing of meat.

Phase 1B: Lower levels: South M-O in which domestic cattle have been introduced and cooking was carried out in pots. Heavy processing of sheep carcasses occurred, cooked in pots on hearths. Domestic and wild cattle are found in feasting contexts. There was more burial in houses and more symbolic elaboration. Houses gradually got larger and there were more activities going on inside them. Obsidian flakes continued to be used.

Phase 2: Later levels: South P-T in which there were more domestic cattle, a heavier dependence on domestic sheep, cooking with pottery and the filleting of meat (based on the evidence of cut marks on bones—Lemorini and D'Errico 2014, Demirergi *et al.* 2014). There were more activities taking place in an around still larger houses, but less burial and wild animal installations. Obsidian was now made into blades used to fillet meat cooked as stews in pots.

In the following analyses two types of cost and two types of benefit are considered, including nutritional, material and social components. The two benefits are calories obtained from food, and prestige within the social network of a house, house group, housing sector, or in the whole Çatalhöyük community. The two costs are labor, and the maintenance of social networks, for example in providing gifts or investing time at social gatherings. The relational costs and benefits are each graded on a scale 0 none, 1 low, 2 moderate, 3 high, 4 very high.

The four cost and benefit values given for each relation between nodes in the network are based on interpretation of the archaeological evidence. To what extent is it possible to estimate the relational costs and benefits? The following examples demonstrate the types of arguments that have been made in relation to the tanglegram networks shown in Figs. 10, 11, and 12.

In phase 1A consider the link between sheep and clay balls. There is archaeological evidence for heavy processing of domesticated sheep carcasses to produce meat that is cooked on the bone, and to obtain marrow, fat, grease using clay balls. As described above, our inference is that animal products were heated by placing clay balls in the oven and then placing the heated balls and meat products in a basket or other container (Atalay 2005). This intensive processing is interpreted (on the basis of the ethnographic

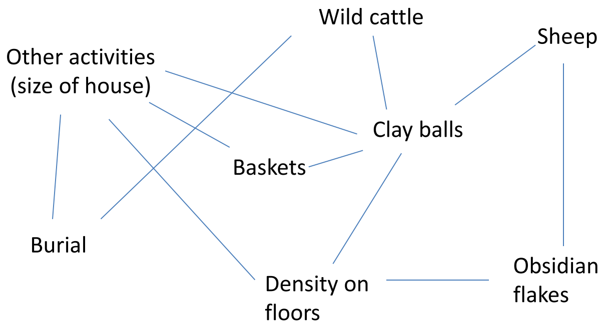


Fig. 10 The links studied in Phase 1A

and experimental work surveyed by Atalay showing the high efficiency of the process) as having produced a very high number of calories per person (score 4 for calories), but there are high labor costs because of the need to watch over the cooking, to change the balls, to break up bone into small pieces to retrieve marrow, fat, and grease (score 3 for labor). There is low social prestige because the processing is done indoors, in unmarked areas of the house (that is in parts of the house that have less symbolic decoration and little ritual), and domestic sheep do not have high social status as can be seen from their absence from symbolism and art and ritual (score 1 for social prestige). There is much archaeological evidence in terms of artifact patterning that processing and cooking of domestic sheep occur at the house level as part of daily routines. As a result, very little extra investment is needed in maintaining this small network, and there is little evidence of domestic sheep being involved in special events in larger social groups (score 1 for network costs). The overall relational benefit less cost is 1 for the link between clay balls and sheep.

As another example, consider the link between other activities and cooking pottery in phase 1B. The increase in the number of activities taking place inside houses can be assessed in terms of the increasing size and internal differentiation of houses. There is good evidence for the gradual increase in house size and internal differentiation, as part of wider regional trends (Byrd 1994). Although this was a ceramic phase there were very few pots in circulation, perhaps one per house and there is no evidence that they were made inside houses. The use of mineral tempered cooking pots rather than clay balls and baskets allowed more space and time for other activities (since, as noted

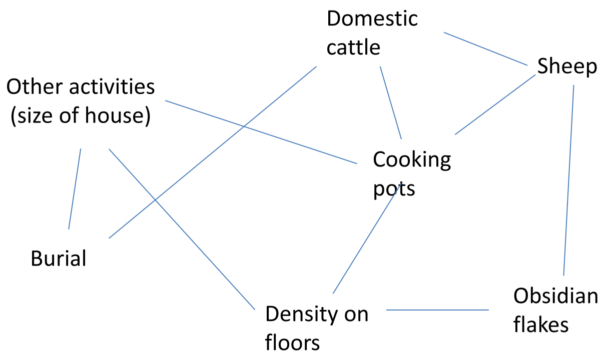


Fig. 11 The links studied in Phase 1B

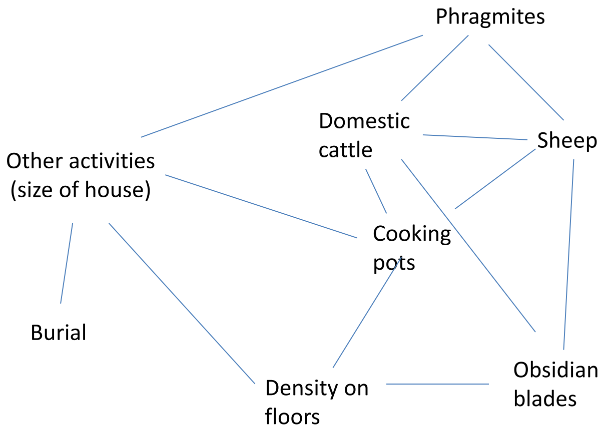


Fig. 12 The links studied in Phase 2

above, cooking pots can act as delegates for the cook). Other activities in the house such as tending the hearth and stacking fuel do contribute to cooking in pots, and the organization of other activities has to leave time and space for cooking with pots, so the link between other activities and pottery does contribute to calorie intake although not directly (score 2 for calories). Other activities are less involved in maintaining pots in cooking than clay balls (score 1 for labor costs). There is no evidence of prestige involved in pottery among the activities in the house. The pottery is not marked or decorated and it is used in unmarked parts of houses (score 1 for social prestige), and the networks involved in the links between pottery and other activities in the house are small scale but with some extension outside the house (score 2 for network costs). The overall relational benefit less cost is 0 for the link between other activities and pottery.

As a final example in phase 2, consider the link between sheep and obsidian blades. In the upper part of the sequence obsidian blades were used instead of flakes. These are more efficient at cutting meat in the sense that more cutting edge is produced per equivalent block of obsidian (Sheets and Muto 1972). The blades were used to fillet meat off the bone (based on cut mark evidence and use wear evidence) so they played an important role. The meat was then boiled in pots. Percussion blade techniques are more difficult and involved specialized labor, partly in-house and partly obtained by exchange (Carter and Milić 2013). Obsidian blades thus contributed significantly to meat consumption and thus to calorie intake (score 3 for calories), but the labor costs in the production of the blades and the filleting of meat off the bone were high (score 3 for labor). Sheep did not have high prestige but the use of fine blades to process meat may have attracted moderate social prestige (score 2 for social prestige). The social networks involved in obsidian exchange were very widespread and complex, but the networks involved in cutting sheep meat off the bone were small scale (score 3 for network costs). The overall relational benefit less cost is 0 for the link between sheep and obsidian blades.

The scores ascribed arise from a systematic heuristic process that is necessarily complex. In the examples given above, there is use of ethnographic analogy and experimental data. But most of the scorings derive from detailed contextual knowledge of a site on which there has been large scale excavation over a long period of time. For example, the low score for social prestige for processing domesticated sheep bones in phase 1A is assigned because of much other evidence that the southern parts of the house in which processing residues are found are not surrounded in decoration, symbolism, and ritual in contrast to the northern parts of houses (Hodder and Cessford 2004). Similarly in phase 1B, pottery is undecorated and is used in the southern parts of the house where the hearth occurs and where pots are sometimes set into the plaster floors. So cooking with pots is given a low score in terms of social prestige. In phase 2 the use of blades to process sheep meat is given a slightly higher score because of the evidence from the site that obsidian blades involved some amount of specialized production and they were often found in special deposits (for example in niches or along the edges of platforms). The scorings are transparent and open to critique and re-evaluation in relation to the evidence from the site.

Table 1 summarizes the relational costs and benefits for all the links shown in Figs. 10, 11, and 12. The links included in the different phases are similar and there are an equivalent number in the three phases (11, 10, 10). The overall benefit less cost in phase 1A is −13, in phase 1B −6, and in phase 2–4. The absolute values are of little interest in themselves; it is the relative values that are the foci of this study. Through time this particular set of links becomes less costly in relation to benefits. Why is this? We can consider the effect of each variable in turn. For example, if we consider all the one-distance links to clay balls in phase 1A the overall benefit-cost is −7. But for pottery in phase 1B the benefit-cost jumps to +3. It is +2 in phase 2. These results demonstrate very clearly that pottery is attractive as a new cooking technology because it is much less costly and provides more benefits, both material and social, than clay balls.

The network analysis indicates that the use of clay balls for cooking in phase 1A was time consuming and the processing of carcasses with obsidian flakes was relatively inefficient. As a result the amount of time and space that could be devoted to other activities in the house was restricted. There was thus a high level of entanglement that limited what could be achieved. In phase 1B there was some release from this entanglement because the shift to cooking pottery allowed a wider range of activities in the house. In phase 2 there are benefits from more efficient animal processing with obsidian blades and cooking pottery.

As in the earlier analysis of chainworks, these conclusions from the analysis of relational costs and benefits are very sensitive to the numbers of variables included. For example, in phase 2, we know that there was an increase of phytoliths of the reed *Phragmites australis* (Ryan 2013); this has been interpreted in terms of the aggressive expansion of this species in disturbed ground around the site, partly caused by the more intensive grazing of sheep and cattle by the site. This invasive species would have had to be managed by cutting back using obsidian blades. If we add in the relational costs and benefits of the links between *Phragmites* and domestic cattle, sheep, and other activities then the overall benefits-costs shifts from −4 to −15.

The more variables are considered, the more we can appreciate how things get entangled up in each other. If we move from considering costs and benefits in terms of optimizing a few variables (for example, in relation to technological specialization see Stevens and McElreath 2015), to evaluating costs and benefits in relation to the entanglements as a whole, we find that certain things become nodal in the network of entanglements such that they dominate or entrap. For example, in the case of obsidian blades, these allow more efficient filleting of meat so that meat off the bone

Table. 1 The relational costs and benefits for all the links shown in Figs. 10, 11, and 12

	Labor costs	Network costs	Calorie benefits	Prestige benefits	Benefits-costs
Clay balls/sheep	3	1	4	1	1
Sheep/obsidian flakes	1	1	1	0	−1
Obsidian flakes/floor residues	3	2	1	1	−3
Floor residues/clay balls	3	2	1	1	−3
Floor residues/other activities	2	2	2	1	−1
Other activities/clay balls	3	2	1	1	−3
Other activities/baskets	2	2	2	1	−1
Other activities/burial	2	3	0	3	−2
Burial/wild cattle	1	3	2	4	2
Wild cattle/clay balls	1	1	1	2	1
Baskets/clay balls	4	2	2	1	−3
Totals Phase 1A	25	21	17	16	−13
Domestic cattle/sheep	3	4	4	2	−1
Domestic cattle/cooking pots	2	1	2	2	1
Domestic cattle/burial	4	4	2	4	−2
Sheep obsidian flakes	1	2	2	1	0
Sheep/cooking pots	2	3	4	1	0
Obsidian flakes/floor residues	3	2	2	2	−1
Cooking pots/floor residues	1	2	4	1	2
Floor residues/other activities	3	2	3	1	−1
Other activities/burial	2	3	0	1	−4
Cooking pots/other activities	1	2	2	1	0
Totals Phase 1B	22	25	25	16	−6
Domestic cattle/sheep	4	4	4	2	−2
Domestic cattle/cooking pots	3	2	4	3	2
Domestic cattle/obsidian blades	3	3	3	2	−1
Sheep/cooking pots	3	2	4	1	0
Sheep/obsidian blades	3	3	3	2	−1
Cooking pots/floor residues	2	2	2	2	0
Obsidian blades/floor residues	3	2	2	2	−1
Cooking pots/other activities	2	2	2	2	0
Floor residues/other activities	3	2	2	1	−2
Other activities/burial	1	2	2	2	1
Totals Phase 2	27	24	28	19	−4

can be cooked in larger quantities in small pots, but they also allow more efficient cutting back of reeds. By the end of phase 2, many processes would have become dependent on obsidian blades so that it would have difficult to do without them. It would have been difficult to "go back" to using obsidian flakes. Similarly, through time at Çatalhöyük the affordances of pottery become increasingly used (Hodder 2014c). Initially important as containers and for cooking, they later become used for storage and they came to take on important social roles and be richly decorated. Initially, perhaps in phase 1b, it would have been possible to go back to cooking with clay balls. But very quickly, so much became entangled with, dependent on, pottery that it would have been very "costly" (in material and social terms) to go back. Humans and pots had become so entangled that it would have been difficult to get out of this particular "path dependency" (Wilsford 1994). The various network measures described in this paper contribute to an understanding on this entrapment.

Conclusion

This account has involved the differentiation of three types of entanglement that can be represented and explored using methods taken from the network sciences.

(1) The first type is that every HT, TH, TT, or HH dependence is tangled up in other HT, TH, TT, and HH dependencies. Any relationship between particular humans and things is tied up in the temporalities and chains of other things with which they interact. A network approach allows a movement away from individual humans and artifacts to explore how those individual things and humans are produced within and constrained by the wider entanglements.

(2) But it is not just that humans and things are linked to other humans and things in "interactions" (Schiffer 1987) or equipmental totalities (Heidegger 1973). These larger spheres of entanglements are themselves structured in such a way that certain nodes are more significant than others for particular tasks. In the same way that network analysis allows analysis of the airport "hub" that a passenger has to go through to get from A to B, so it allows study of how individual humans or things are dependent on particular nodes, such as the house or food in the Çatalhöyük example. The centrality of nodes such as houses and food, and the operational chains that lead into and out of them, themselves create a structure that network analysis can assist in describing.

(3) A third type of entanglement is the dialectic of dependence and dependency that may exist between two humans and things in terms of the affordances and demands that they make on each other. We have already used the example of the ways in which the domestication of cereals entangled humans into the labor of winnowing and threshing. Humans come to depend on things that depend on them, and make demands on them. The study of networks of relational costs and benefits allows exploration of these more complex dependencies.

We started this paper with the aim of exploring the extent to which formal network analysis could be used to study aspects of entanglement. We have used the detailed evidence from the excavations of Çatalhöyük in order to evaluate various forms of network analysis. In the most general of terms, it seems that formal network analysis has much to offer on the study of the first type of entanglement. Despite problems associated with the definitions of nodes and boundaries, network analysis provides ways of summarizing and visualizing thing-thing and human-thing dependencies. Networks can be produced that are based on dependency matrices, as in Fig. 2. In contrast to networks that focus on social or cultural interaction, we can term such networks tanglegrams. The tanglegrams shown in Figs. 2 and 4 summarize complex relationships between large numbers of variables in clear and simple ways. They encapsulate the research expressed in many thousands of narrative pages of text. They provide clear summary information that allows new patterns to be seen and further explored.

The network analyses also allow exploration of the second type of entanglement. In particular, the ego networks in Fig. 4 show that the structure of various forms of centrality can be studied (Fig. 5). In these examples, the importance of the house was demonstrated, building on previous work, by tracing the shifts in degree and betweenness through time. Entanglements are also structured by the presence of long interlinked operational chains. These chainworks can be explored through network analysis of paths, but we have so far concluded that there are difficulties here in that there are analytical advantages in keeping simultaneous paths separate rather than linking them into shortest paths. We have so far found that the most informative, productive, and robust approach is to identify simple upstream-downstream sequences and then to explore the links between them (Figs. 6 and 7). The problems we have identified seem to correspond with wider discussion of the limited focus on temporal structure within social or actor network analyses (Latour 2005, although see Pentland and Feldman 2007).

Finally, network analysis in the forms in which it is used most frequently in archaeology does not describe well the tensions between dependence and dependency that are at the heart of entanglement. However, when allied with quantitative coding of the relational costs and benefits between specific operations within a tanglegram, it is possible to conduct productive analyses that explore the ways in which certain humans, things, or operations increase or decrease local or wider entanglements. It is possible to explore how the affordances of, for example, cooking pottery produce temporary disentanglement, and thus openings for other changes to occur. It is possible to explore how cooking meat with clay balls led to constraint and limitation on what could take place inside houses. Such analysis, however, depends on having access to rich data sets in which the links between humans and things have been well studied. It is only in these ways that contextual evidence can be used to substantiate the quantitative coding of specific relational costs and benefits.

Acknowledgments This paper is a result of research funded by the Netherlands Organisation for Scientific Research (NWO) as part of the Island Networks project (grant agreement no. 360-62-060). We would like to thank the Graduate School of Archaeology of the Faculty of Archaeology at Leiden University for organizing a workshop at which the idea of networks and entanglements was first explored. We thank Daniel Weidele for advising us and providing feedback on the chainworks study. We are very grateful to Brian Codding and Carl Knappett for comments on an earlier version of this paper, and to five anonymous reviewers. We are also grateful to Douglas Baird for his help and advice in relation to the Boncuklu tanglegram.

References

Atalay, S. (2005). Domesticating clay: the role of clay balls, mini balls and geometric objects in daily life at Çatalhöyük. In I. Hodder (Ed.), *Changing Materialities at Çatalhöyük: Reports from the 1995–99*

Seasons (pp. 139–168). Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Baird, D. (2007a). The Boncuklu Project: the origins of sedentism, cultivation and herding in central Anatolia. *Anatolian Archaeology, 13*, 14–18.

Baird, D. (2007b). Pınarbaşı: from Epipalaeolithic camp site to sedentarising village in central Anatolia'. In M. Özdoğan & N. Başgelen (Eds.), *The Neolithic in Turkey: new excavations and new discoveries* (pp. 285–311). Istanbul: Arkeoloji ve Sanat Yayinları.

Bettinger, R. L., Winterhalder, B., & McElreath, R. (2006). A simple model of technological intensification. *Journal of Archaeological Science, 33*, 538–545.

Bogaard, A., Charles, M., Livarda, A., Ergun, M., Filipović, D., & Jones, G. (2013). The archaeobotany of mid-later occupation levels at Neolithic Çatalhöyük. In I. Hodder (Ed.), *Humans and Landscapes of Çatalhöyük: Reports from the 2000–2008 Seasons* (pp. 93–128). Los Angeles: Cotsen Institute.

Borgatti, S. P., & Halgin, D. S. (2011). On network theory. *Organization Science, 22*(5), 1168–1181.

Borgatti, S. P., Mehra, A., Brass, D. J., & Labianca, G. (2009). Network analysis in the social sciences. *Science, 323*(5916), 892–895.

Brandes, U., Robins, G., McCranie, A., & Wasserman, S. (2013). What is network science? *Network Science, 1*(1), 1–15.

Brandes, U., & Wagner, D. (2004). Analysis and visualization of social networks. In M. Jünger & P. Mutzel (Eds.), *Graph drawing software* (pp. 321–340). Berlin: Springer Verlag.

Brughmans, T. (2010). Connecting the dots: towards archaeological network analysis. *Oxford Journal of Archaeology, 29*(3), 277–303.

Brughmans, T. (2013). Thinking through networks: a review of formal network methods in archaeology. *Journal of Archaeological Method Theory, 20*, 623–662.

Brysbaert, A. (2007). Cross-craft and cross-cultural interactions during the Aegean and Eastern Mediterranean Late Bronze Age. In *Mediterranean crossroads* edited by Sophia Antoniadou and Anthony Pace, (pp. 325–359). Pierides Foundation

Butts, C. T. (2009). Revisiting the foundations of network analysis. *Science, 325*, 414. doi:10.1126/science.1171022.

Byrd, B. (1994). Public and private, domestic and corporate: the emergence of the Southwest Asian village. *American Antiquity, 59*, 639–666.

Carter, T. and Milić, M. (2013). The chipped stone. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons* (417–78). Los Angeles

Collar, A., Coward, F., Brughmans, T., & Mills, B. J. (2015). Networks in archaeology: phenomena, abstraction, representation. *Journal of Archaeological Method and Theory, 22*(1), 1–32.

Crown, P. L., & Wills, W. H. (1995). The origins of Southwestern ceramic containers: women's time allocation and economic intensification. *Journal of Anthropological Research, 51*(2), 173–186.

Demirergi, G.A., Twiss, K.C., Bogaard, A., Green, L., Ryan, P., Farid, S. (2014). Of bins, basins and banquets: storing, handling and sharing at Neolithic Çatalhöyük. In I. Hodder (ed.), *Integrating Çatalhöyük: Themes from the 2000–2008 Seasons* (91–108). Los Angeles

Dietler, M. (1998). Consumption, agency, and cultural entanglement: theoretical implications of a Mediterranean colonial encounter. In J. Cusick (Ed.), *Studies in culture contact: interaction, culture change, and archaeology* (pp. 288–315). Carbondale, IL: Centre for Archaeological Investigations.

Dietler, M. (2010). *Archaeologies of colonialism. Consumption, entanglement, and violence in ancient Mediterranean France*. Berkeley, CA: University of California Press.

Doherty, C. (2013). Sourcing Çatalhöyük's clays. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons* (51–66). Los Angeles.

Doherty, C., Tarkan, D. 2013. Pottery production at Çatalhöyük: a petrographic perspective. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. 9183–92). Los Angeles.

During, B.S. (2006). *Constructing Communities: Clustered Neighbourhood Settlements of the Central Anatolian Neolithic ca. (8500–5500). Cal. BC.* PhD thesis, Leiden University

Edensor, T. (2011). Entangled agencies, material networks and repair in a building assemblage: the mutable stone of St Ann's Church, Manchester. *Transactions of the Institute of British Geographers NS, 36*, 238–52.

Everett, M., & Borgatti, S. P. (2005). Ego network betweenness. *Social Networks, 27*, 31–38.

Farid, S. (2014). Timelines: phasing Neolithic Çatalhöyük. In I. Hodder (ed.), *Çatalhöyük Excavations: The 2000–2008 Seasons*. (91–130). Los Angeles.

Freeman, L. C. (1982). Centred graphs and the structure of Ego networks. *Mathematical Social Sciences, 3*(3), 291–304.

Fuller, D. Q., Allaby, R. G., & Stevens, C. (2010). Domestication as innovation: the entanglement of techniques, technology and chance in the domestication of cereal crops. *World Archaeology, 42*(1), 13–28.

Heidegger, M. (1973). *Being and time*. Oxford: Blackwell.

Hodder, I. (Ed.). (1996). *On the Surface: Çatalhöyük 1993–1995*. Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Hodder, I. (Ed.). (2000). *Towards reflexive method in archaeology: the example at Çatalhöyük*. Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Hodder, I. (Ed.). (2005a). *Çatalhöyük perspectives: themes from the 1995–1999 seasons*. Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Hodder, I. (Ed.). (2005b). *Inhabiting Çatalhöyük: reports from the 1995–1999 seasons*. Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Hodder, I. (Ed.). (2006a). *Changing materialities at Çatalhöyük: reports from the 1995–99 seasons*. Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Hodder, I. (2006b). *The Leopard's tale: revealing the mysteries of Çatalhöyük*. London: Thames and Hudson.

Hodder, I. (Ed.). (2007). *Excavating Çatalhöyük: South, North and KOPAL area reports from the 1995–1999 seasons*. Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Hodder, I. (2012). *Entangled: an archaeology of the relationships between humans and things*. Oxford: Wiley Blackwell.

Hodder, I. (ed.) (2013a): *Humans and Landscapes of Çatalhöyük: Reports from the 2000–2008 Seasons*. Los Angeles.

Hodder, I. (ed.) (2013b): *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. Los Angeles.

Hodder, I. (ed.) (2014a): *Çatalhöyük Excavations: The 2000–2008 Seasons*. Los Angeles.

Hodder, I. (ed.) (2014b): *Integrating Çatalhöyük: Themes from the 2000–2008 Seasons*. Los Angeles.

Hodder, I. (2014c). Çatalhöyük: the leopard changes its spots. A summary of recent work. *Anatolian Studies, 64*, 1–22.

Hodder, I., & Cessford, C. (2004). Daily practice and social memory at Çatalhöyük. *American Antiquity, 69*, 17–40.

Hodder, I., & Pels, P. (2010). History houses: a new interpretation of architectural elaboration at Çatalhöyük. In I. Hodder (Ed.), *Religion in the emergence of civilization. Çatalhöyük as a case study* (pp. 163–186). Cambridge: Cambridge University Press.

Ingold, T. (2000). *The perception of the environment: essays on livelihood, dwelling and skill*. Psychology Press.

Ingold, T. (2010). *Bringing Things Back to Life: Creative Entanglements in a World of Materials.* NCRM Working Paper, (1–15). http://eprints.ncrm.ac.uk/1306/.

Knappett, C. (2011). *An archaeology of interaction: network perspectives on material culture and society.* Oxford University Press.

Knappett, C. (ed). (2013). *Network analysis in archaeology: New approaches to regional interaction*. Oxford University Press.

Kuijt, I., & Goring-Morris, A. N. (2002). Foraging, farming, and social complexity in the Pre-Pottery Neolithic of the southern Levant: a review and synthesis. *Journal of World Prehistory, 16*, 361–440.

Last, J. (2005). Pottery from the East Mound. In I. Hodder (Ed.), *Changing Materialities at Çatalhöyük: reports from the 1995–99 seasons* (pp. 101–138). Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.

Latour, B. (2005). *Reassembling the social: an introduction to actor-network-theory.* Oxford: Oxford University Press.

Lemonnier, P. (Ed.). (1993). *Technological choices: transformation in material cultures since the Neolithic*. London: Routledge.

Lemorini, C. and D'Errico, D. (2014). Use-wear analysis of chipped stone tools. *Çatalhöyük 2014 Archive Report* http://www.catalhoyuk.com/archive_reports/.

Leroi-Gourhan, A. (1943). *L'Homme et la Matière*. Paris: Albin Michel.

Love, S. 2013. An archaeology of mudbrick houses from Çatalhöyük. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons* (81–96) Los Angeles.

Marciniak, A., & Czerniak, L. (2007). Social transformations in the Late Neolithic and the Early Chalcolithic periods in central Anatolia'. *Anatolian Studies, 57*, 115–30.

Matthews, W. (2005). Micromorphological and microstratigaphic traces of uses and concepts of space. In I. Hodder (Ed.), *Inhabiting Çatalhöyük: reports from the 1995–1999 seasons* (pp. 355–398). Cambridge: McDonald Institute for Archaeological Research/British Institute of Archaeology at Ankara Monograph.
Mellaart, J. (1967). *Çatal Hüyük: a neolithic town in Anatolia*. London: Thames and Hudson.
Mills, B. 2014. Relational networks and religious sodalities at Çatalhöyük. In I. Hodder (ed.), *Religion at Work in a Neolithic Society: Vital Matters*. (159–86) Cambridge.
Mol, A. A. A., Hoogland, M. L. P., & Hofman, C. L. (2015). Remotely local: ego-networks of late pre-colonial (AD 1000–1450) Saba, Northeastern Caribbean. *Journal of Archaeological Method and Theory, 22*(1), 275–305.
Pachucki, M. A., & Breiger, R. L. (2010). Cultural holes: beyond relationality in social networks and culture. *Annual Review of Sociology, 36*, 205–224.
Pentland, B. T., & Feldman, M. S. (2007). Narrative networks: patterns of technology and organization. *Organization Science, 18*(5), 781–795.
Pitter, S., Yalman, N., Evershed, R. (2013). Absorbed lipid residues in the Çatalhöyük pottery. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. (193–200) Los Angeles.
Rogers, E. M. (2010). *Diffusion of Innovations*. New York: Simon and Schuster. 4th edition.
Russell, N., Twiss, K.C., Orton, D., Demirergi, A. (2013). More on the Çatalhöyük mammal remains. In I. Hodder (ed.), *Humans and Landscapes of Çatalhöyük: Reports from the 2000–2008 Seasons*. (213–58). Los Angeles.
Ryan, P. 2013. Plant exploitation from household and landscape perspectives: the phytolith evidence. In I. Hodder (ed.), *Humans and Landscapes of Çatalhöyük: Reports from the 2000–2008 Seasons*. (163–90). Los Angeles.
Schiffer, M. B. (1987). *Formation processes of the archaeological record*. Albuquerque: University of New Mexico Press.
Schiffer, M. B. (2004). Studying technological change: a behavioral perspective. *World Archaeology, 36*(4), 579–585.
Scott, J. (2000). *Social network analysis: a handbook*. London: Sage.
Sheets, P. D., & Muto, G. R. (1972). Pressure blades and total cutting edge: an experiment in lithic technology. *Science, 175*(4022), 632–34.
Shillito, L. M., Matthews, W., Almond, M. J., & Bull, I. D. (2011). The microstratigraphy of middens: capturing daily routine in rubbish at Neolithic Çatalhöyük, Turkey. *Antiquity, 85*(329), 1024–1038.
Stahl, A. B. (2002). Colonial entanglements and the practices of taste: an alternative to logocentric approaches. *American Anthropologist, 104*(3), 827–845.
Stevens, N. E., & McElreath, R. (2015). When are two tools better than one? Mortars, millingslabs, and the California acorn economy. *Journal of Anthropological Archaeology, 37*, 100–111.
Strathern, M. (1996). Cutting the network. *Journal of the Royal Anthropological Institute, 2*(3), 517–535.
Terrell, J. E. (1977). Human biogeography in the Solomon islands. *Fieldiana Anthropology, 68*(1), 1–47.
Thomas, N. (2009). *Entangled objects: exchange, material culture, and colonialism in the Pacific*. Harvard University Press.
Tung, B. (2013). Building with mud: an analysis of architectural materials at Çatalhöyük. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. (67–80). Los Angeles.
Ugan, A., Bright, J., & Rogers, A. (2003). When is technology worth the trouble? *Journal of Archaeological Science, 30*(10), 1315–1329.
Vasić, M., Bains, R., Russell, N. (2014). Dress: a preliminary study of bodily ornamentation at Çatalhöyük. In I. Hodder (ed.), *Integrating Çatalhöyük: Themes from the 2000–2008 Seasons*. (197–220). Los Angeles
Watts, C. (2013). *Relational archaeologies. Humans, animals, things*. London: Routledge.
Wilsford, D. (1994). Path dependency, or why history makes it difficult but not impossible to reform health care systems in a big way. *Journal of Public Policy, 14*(03), 251–283.
Winterhalder, B. (1983). Opportunity-cost foraging models for stationary and mobile predators. *American Naturalist, 122*(1), 73–84.
Yalman, N., Tarkan, D., Gultekin, H. (2013). The Neolithic pottery of Çatalhöyük: recent studies. In I. Hodder (ed.), *Substantive Technologies at Çatalhöyük: Reports from the 2000–2008 Seasons*. (147–82). Los Angeles.