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RESEARCH

Convergent Evolution of Prehistoric Technologies: the Entropy and Diversity of Limited Solutions

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Abstract

Linking the likelihood of convergent evolution to the technologies' complexity, this paper identifies the scales of technological diffusion and convergence, *i.e.*, the evolving of structures that are similar, but not related to a common "ancestor." Our study provides quantitative measures for understanding complexity and connectivity in technologies. The utility of our approach is exemplified through the case study of Cucuteni-Tripolye pottery kilns in Chalcolithic Southeastern Europe. The analysis shows that technological evolution has to be scaled to the "technologically important" (in quantitative terms) component parts, whose introduction shapes a ground for extinction and self-evolvement caused by the cascade effects along technological design structure. Similar technological solutions to the technological design structure engender the spread of similar devices in various locations. Surprisingly, such a broad distribution may be the result of relatively low internal diversity, rather than arising from higher efficiency. This gives some reasons for the underestimation of convergence as a mechanism for evolution of technology in current prehistoric archaeology.

Keywords Complexity · Technological design structure · Convergence · Archaeological diversity · Pottery kilns · Cucuteni-Tripolye cultural complex

Introduction

Human evolutionary success is, to a large extent, supported by our ability to develop and use technologies. Most broadly and most basically defined as "a means to carry out human purpose" (Arthur, 2009), technology becomes more and more complex

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as time passes. Our hominid ancestors used stone tools for hunting and gathering. Modern *Homo sapiens* experiment with thermonuclear fusion, launch artificial satellites, and spend their free time posting photos on social networks.

The development of technology does not necessarily follow the path of biological evolution (Arthur, 2009; Bentley & O'Brien, 2017; Roux, 2010; Shennan, 2013; Solée et al., 2013; Wagner & Rosen, 2014). Although seeming very different, evolutionary studies in the development of the telegraph, radio, bicycles, and cars can inform the identification of patterns explaining the evolution of flint points or ceramic vessels (Gjesfjeld et al., 2016; Hollenback & Schiffer, 2010; Kempe & Mesoudi, 2014; Lake & Venti, 2009; Mesoudi, 2010; Mesoudi & O'Brien, 2008; O'Brien & Bentley, 2011; Richerson & Christiansen, 2013; Schiffer, 1993, 1996, 2005, 2010).

Similar cultural traits can evolve in alternative ways: "homology" and "convergence." Homology presumes a common "ancestor" in traits, while convergence covers the evolving of artefacts that are similar in form and/or function, but not related to a common "ancestor" (Charbonneau, 2018). Archaeological evidence exemplifies both of these competing options. For instance, hunter-gatherers in South-Eastern Europe borrowed ceramic pottery from early farmers, descendants of migrants from Anatolia (e.g., Endo et al., 2021). Alternatively, the tradition of Jōmon pottery manufacturing, dating back to ca. 12500 BP, was independently developed in East Asia (Gibbs, 2015; Imamura, 1996). The latter example of convergence is obvious due to the spatial isolation and significant chronological gap between the two traditions. However, the vast majority of cases require much denser spatio-temporal resolutions, necessitating new approaches. Apart from distinguishing the morphological similarity of convergent evolution (resulting from independent invention) or homology (resulting from common ancestry), it is also important to explain how processing techniques impact products (Charbonneau, 2018).

Acknowledging the complex paths of prehistoric technologies' diffusion, we argue that their convergent evolution is often significantly underestimated in current archaeological theory. An exception is represented by studies in the convergence of stone tools, with a solid theoretical, methodological, and empirical basis (e.g., O'Brien et al., 2018), but even here ultra-diffusionist explanations are still common. The homology/convergence issues are most frequently approached with the application of phylogenetic analysis confirming or rejecting hypotheses on common ancestry (e.g., Lipo et al., 2006). Alternative approaches include the construction of theoretical morphospaces (McGhee, 2018), or morphocentric models further developing theoretical morphospaces (Charbonneau, 2018). Buchanan and co-authors (2018) suggested the evaluation of likelihood of the North American points' convergence by isolating pairs of points in a paradigmatic classification, where spatial and temporal isolation identified two types of convergence. These are functional convergence, referring to the regional environment, and neutral convergence less likely to be dealing with adaptation.

Developing the idea that technological innovation results from recombination, either a consequence or not of shared ancestry, this paper gives reasons for the underestimation of convergence by showing that some technological innovations are more probable than others depending on the technologies' complexity. We provide quantitative measures for the technologal complexity by estimating convergence scores showing to what extent some modifications of technologies are more likely to occur than others. This study also introduces the technological significance factor explaining *why* particular modifications of technologies are more likely to occur independently than others, and *how* the connectivity of component parts contributes to the technology's internal diversity. The utility of our quantitative approach is exemplified through the case study of Cucuteni-Tripolye pottery kilns in Chalcolithic Southeastern Europe.

Research Hypothesis and Method

Before we can analyse the relationship between convergent evolution and technological complexity, we shall begin with a brief overview of what constitutes a "technology." Archaeological research often compares the complexity of different phenomena in a descriptive way, as "more simple" and "more complex," but quantitative measures of complexity have been developed (Perreault et al., 2013), as will be explained in the 'Method' subsection below.

Research Hypothesis

For a better understanding of technology in which to frame our research hypothesis, the following brief discussion of the complex character of technology calls heavily upon W.B. Arthur's (2009) book *The Nature of Technology*. A number of ideas expressed in this book were developed independently (convergently) by other authors (Johnson, 2010; Ogburn & Thomas, 1922), and we refer to them when appropriate.

Arthur (2009) supplements his broadest definition of technology as "a means to carry out human purpose" by two more definitions. These are technology as an "assemblage of practices and components" and as "the entire collection of devices and engineering practices available to a culture" (p. 28). According to this understanding, technology originates as a new concept and develops by modifying its internal parts. The internal component parts, sub-parts, etc., the explicit material culture of the technology, have their own specific function contributing to its overall purpose. Technological solutions may require further solutions, making new component parts available and creating new technological domains. In this respect we deal with self-evolving phenomena (Arthur, 2009). Following Arthur's concept, evolution of technology is a product of re-arrangement (re-connection) of its component parts. In other words, innovations most frequently result from recombination (Arthur, 2009; also see: Bentley & O'Brien, 2017; Bentley et al., 2011; Charbonneau, 2016; Kauffman, 2000; Kohler, 2011; Strumsky & Lobo, 2015).

Arthur's notion of technological complexity can be understood as internal diversity arranged into a whole (Bentley et al., 2011). Most simply, the modules, which maintain their function relatively independently, (see Charbonneau, 2016), account for the variability of modification of each component part (e.g., McGhee, 2018;

Oswalt, 1976). In other words, each module can vary in some respect through modifications to the technology (Arthur, 2009; Charbonneau, 2016; Mesoudi, 2011a; O'Brien & Lala, 2023). Modularity is most easily seen with the aid of a Design Structure Matrix (Browning, 2001; Steward, 1981). The design structure matrix displays the relationships between components of a system in a compact, visual format. Component parts are represented by the elements along the diagonal. Off-diagonal elements signify the dependency of one component part on another. Reading down a column reveals input sources, while reading across a row indicates output sinks. In practise, we gain little for a system as technologically simple as in our case study for which Fig. 2 suffices.

Component parts of technologies are improved both as a result of accumulated intentional modifications and as accidental innovations (Boyd et al., 2011, 2013; Richerson & Boyd, 2005; Roux, 2010). Considering that these components of technologies do not reproduce themselves, but are being reproduced by a number of producers for a number of consumers, the variability of these components is significantly impacted by the population size and structure (Bentley et al., 2011; Boyd & Richerson, 2022; Boyd et al., 2013; Creanza et al., 2017; Crema & Lake, 2015; Deffner et al., 2022; Derex & Boyd, 2016; Derex & Mesoudi, 2020; Diachenko & Sobkowiak-Tabaka, 2022; Edinborough, 2009; Henrich, 2004; Kempe & Mesoudi, 2014; Lycett & Norton, 2010; Powell et al., 2010; Richerson et al., 2009; Shennan, 2001, 2013, 2018; Sterelny, 2020; Walker et al., 2021). If certain component parts are replaced over the duration of a device's functioning, the device's diversity may be also impacted by the component parts' life use (Diachenko & Sobkowiak-Tabaka, 2022; Kuhn, 2022; Perreault, 2019; Schiffer, 1987; Schott 1989; 2010). For instance, consider bow and arrows. Arrows are replaced during the "bow-and-arrows" device functioning. Arrowheads, being a subject of modification and accidental innovations, impact the overall device's diversity for the time of its functioning.

The evolution of technology is not totally random, nor completely predictable, rather representing a gradient between these two extremes. Combination and connectedness provide a technology with a capability for being changed significantly within a limited framework (Johnson, 2010; Kauffman, 2000; O'Brien et al., 2018; O'Brien & Lala, 2023). Since component parts fulfil specific purposes, connectedness operates in opposite directions, both shaping the self-evolving character of technology and limiting the variability of each component part. Let us have a closer look at the connectedness framing the self-evolvement of technology, innovation cascades, and selection.

The term "cascading effects" in innovation flow characterises how innovations in one component-part cause subsequent changes in connected component-parts (Schiffer, 2005). It was understood in archaeology quite early that technology is produced and functions as a sequence of operations. The nineteenth century evolutionist W.H. Holmes pointed out that lithic artefacts found in the quarry are a result of "a series of progressive steps of manufacture", anticipating the processual form – sequence (Schlanger, 2005: 18). Later, this idea was shaped into the concept of *chaîne opératoire* (literally "operational chain"), addressing the process by which raw materials are selected, modified and transformed into cultural products. Although this term originally was developed for studies of stone artefacts, nowadays it is widely used by archaeologists dealing with various materials, e.g., ceramics, metals, textiles. Thus, each artefact or structure can be placed in each stage of the process through the analysis of a technological feature (Pelegrin et al., 1988). Since the production process can be divided into singular sequences or operations, each stage can be considered as part of a whole (Roux, 2009; Soressi & Geneste, 2011). It is notable that A. Leroi-Gouhran (1993:114[1964:164]), on first introducing the term *chaîne opératoire,* defined it as a technique involving actions and tools, organized in a *chain* encoding the operational series, which are unchanging and flexible. Thus, the total number of stages in a "cascade" depends on the stage where the cascade-initiating innovation occurs (Schiffer, 2005).

Of course, innovation cascades flowing through the connected component parts are not unidirectional, being a subject of thought-and-action sequences and feedback loops. Archaeological evidence exemplifies this by so-called complementary tool sets, e.g., arrows and bow, for which decision-making considering one tool is possible only with simultaneous decision-making considering another tool (Hoffecker & Hoffecker, 2017).

Cascading effects typically result in increasing internal diversity followed by the selection and extinction and turnover of component parts (Solée et al., 2013). At best, the selection operating after combining component parts into a technology optimally balances efficiency and production costs (e.g., Bettinger, 2009). However, human behaviour is often far from rational, and, therefore, selective decisions are not optimal in many cases (Bentley & O'Brien, 2015; Bentley et al., 2011; Darley & Kaufmann, 1997; O'Brien et al., 2019; Shennan, 2013; Solée et al., 2013). Declining originality and the extinction of technological designs over time generally correlates with the increasing longevity of surviving models (Gjesfjeld et al., 2016).

The selection operating after a technology has been composed should be distinguished from the selection operating during the composition process (Shennan, 2013). The former operates with innovations, *i.e.*, socially adopted inventions (e.g., O'Brien & Bentley, 2021). The latter operates with inventions (experiments) or, even prior to them, the decision-making process behind inventions. Since component parts are arranged into a technological design structure (see Fig. 2 as our example), a novel component part should be shaped in accordance with its combinatorial 'potential' (Arthur, 2009; Johnson, 2010; Solée et al., 2013). This way connectedness decreases the technology's uncertainty, *i.e.*, decreases the diversity of component parts to the number of options limited by the technology's structure. Given the availability of component parts in a culture, limitation or decreasing uncertainty resulted from combinatorial potential makes the evolution predictable to a certain extent and leads to convergence (Charbonneau, 2018; McGhee, 2018). This statement may be illustrated using the following example. Consider technologies composed of horses and chariots. Small horses move small chariots, big horses move either small or big chariots. The availability of only small horses limits the evolution of 'horse-and-chariot' technology to small horses moving small chariots since they are connected together. Therefore, wherever only small horses are available, the convergent evolution of the latter technology is more likely. Big horses connected to big or small chariots increase the technology's uncertainty because of the variation in chariots. Actual ethno-archaeological examples include house hearths determining the size of cooking pots, the methods and materials of house construction, the use of indoor and outdoor space, and vice versa (Beck et al., 2022). Numerous examples of convergence due to the limited variability in component parts are provided by evolutionary biology (McGhee, 2011).

Hence, the technological complexity increases with the increasing number of modules and variation in each module. However, the involvement of more modules and the increase in their internal variation implies more constraints on modules connection and, therefore, more constraints on the overall technological complexity, providing a certain extent of predictability to the evolution of technologies. This relationship between diversity of component parts and convergence makes possible the following research hypothesis. The likelihood of convergent evolution of a particular technology preconditioned by the availability of all its parts and components is inversely proportional to this technology's internal diversity (Roux, 2010; Shennan, 2013). Therefore, similar or "analogous" technologies of smaller internal diversity are more frequently spread across regions or taxonomically aggregated sites (e.g., across archaeological cultures) than the ones of a greater diversity. It should be noted that, despite a certain subjectivism in their distinguishing and fuzzy borders, 'archaeological cultures' remain a powerful tool of data systematization (e.g., Roberts & Vander Linden, 2011). This comparative perspective should also account for population size and structure (see above). The following section discusses complexity (considered here as internal variability of sequentially connected components) as a quantifiable measure.

Method

The quantification of artefact diversity in archaeology is often approached through entropy, a measure of uncertainty in a system. Consider a "system" X, typically a device, which occurs in many variations v_i, $i=1,2,\ \dots,\ n$. Suppose that a large collection of N of these devices shows the ith variant occurring x_i times, *i.e.*, with frequency $p_i = p\left(v_i\right) = x_i/N$. The 'surprisal' $s\left(p_i\right)$ or 'level of surprise' (Tribus, 1961) of picking an entity of variant i at random from the assemblage is large if p_i is small and vice-versa. Most simply, the choice $s\left(p_i\right) = \ln(1/p_i)$, from which follows $s\left(p_i p_j\right) = s\left(p_i\right) + s(p_j)$, guarantees surprisal to be additive for independent events. The average surprisal that we find on randomly choosing devices from the collection is

$$H(X) = \sum_i p_i s\left(p_i\right) = \sum_i p_i \ln\left(\frac{1}{p_i}\right) = -\sum_i p_i \ln p_i, \tag{1}$$

the Shannon (1948) entropy or Shannon *information* (e.g., Freiberger, 2015). It is related to the minimum number of questions that need to be asked to identify individual entities from a known distribution $p\left(v_i\right)$. The minimum value of $H(X)$ is zero, when one of the p_i equals 1 and all the others are zero, an unambiguous outcome. The maximum value of $H(X)$ is $H(max) = \ln n$, (Hartley, 1928) arising when all candidates are equally likely to be found (we work with natural logarithms, *ln x*, rather than logarithms to base 10, *log x*. In that way, $\exp(\ln x) = x$).

The archaeology of hunter-gatherers, for example, has been represented in a number of successful studies applying Shannon's entropy to estimate the complexity of artefacts and their assemblages based on counting the component parts or counting the number of artefacts' functions (Bobrowski & Ball, 1989; Oswalt, 1976; Schott 1986; 1989; 2010; Wiśniewski et al., 2022), and the production steps of an artefact (Perreault et al., 2013). More recent approaches integrate the analysis of component parts and the relationship between these parts (Buchanan et al., 2018; Hoffecker & Hoffecker, 2017). Further developing the logic of these approaches, especially the studies incorporating the application of conditional and joint entropy (Paige & Perreault, 2022), we suggest the application of joint entropy as an intermediate measure of a component's variability, as follows.

Suppose now that we have another system Y with variants w_j *(j=1,2,,m)* occurring with frequencies $q_j = p(w_j)$ which we combine with X to make a joint system (X,Y). This could be an aggregated device, e.g., horse (X) and cart (Y) or it could be enrichment of a standard device, e.g. a pot, for which X denotes morphology and Y fabrication method. In general, the v_i and w_j are correlated, e.g. small horses pull small carts. Let $p\left(v_i, w_j\right)$ be the joint frequency that a random choice from the (X,Y) system possesses variant v_i from the X system and variant w_j from the Y system. The joint entropy $H(X,Y)=H(Y,X)$ is defined as

$$H(X,Y) = -\sum_{i,j} p(v_i, w_j)\ln p\left(v_i, w_j\right). \tag{2}$$

If the variants of X and Y are independent, $p\left(v_i, w_j\right) = p\left(v_i\right)p\left(w_j\right) = p_i q_j$ and $H(X,Y) = H(X) + H(Y)$. In general,$H(X,Y) \leq H(X) + H(Y)$. The difference (information gain)

$$I(X,Y) = H(X) + H(Y) - H(X,Y) \geq 0 \tag{3}$$

is the *mutual information* of X and Y due to correlations (e.g., Yeung, 2002). Intuitively, mutual information measures the information that X and Y share. That is, how much knowing one of these variables reduces uncertainty about the other. The generalisation to more complicated devices with multiple components follows naturally, with mutual information the information gain determined by the difference between the sum of the individual entropies (termed marginal entropies) and the joint entropy.

We shall argue later that technology, which links X and Y together (literally, with a horse and cart, but usually with rather more subtlety) can be understood through information gain; the higher the information gain the more effective the technology. In practice our data, with its limited numbers of entities, is often too poor to enable us to derive sensible estimates for the large number of joint probabilities required. However, it can be easier to estimate conditional frequencies $p(y|x) = \frac{p(y,x)}{p(x)}$, which are very strongly constrained by their definition as $\sum_{\{y\in Y\}} p(y|x) = 1$. This can be explained by means of conditional entropy *H(Y|X),* the average surprisal of the variants Y, knowing their joint information with X:

$$H(Y|X) = H(Y) - \mathrm{I}(X,Y) \tag{4}$$

The unknowns are now largely reduced to the elementary frequencies. In practice, technologies are introduced sequentially. We can accommodate this by giving the frequencies a time dependence e.g. $p(x) \to p(x, t)$.

It should be noted that this limited use of information remains a somewhat nebulous concept (Sloman, 2013) and we prefer to work with (Shannon) *diversity* rather than Shannon entropy. For the system X this is defined as the simple exponential $D(X) = \exp H(X)$. *D(X)* is understood as the effective number of variations needed to represent the assemblage of devices and is known as *numbers diversity* (Jost, 2006). If all *n* variants are equally likely then $D(X)=n$; if only one occurs, then $D(X)=1$. Otherwise, it takes intermediate values depending on the distribution of occurrences (e.g., Colwell & Chao, 2022). It fulfils the intuitive definition of diversity, that the diversity of two disjoint sets of equal size and diversity is the sum of the individual diversities.

From this viewpoint, the correlations induced by technology reduce the overall diversity, the effective number of variants necessary to describe the system. In similar fashion, we can define the conditional diversity of X and Y as $D(Y|X) = \exp H(Y|X)$. Earlier archaeological studies suggested quantification of the artefact's complexity as a sum of variations in all its component parts. We develop this approach switching from a sum of all variations to their product, when estimating diversity as an exponential of entropy.

Large information gains *I* are correlated with low mutual diversities. As a result, the conditional diversity satisfies

$$D(Y|X) = D(Y)/\Lambda(X, Y) \leq D(Y) \tag{5}$$

where the technology impact factor $\Lambda\,(X, Y)$ is derived directly from the joint information as

$$\Lambda(X, Y) = \exp I(X, Y) \geq 1 \tag{6}$$

That is, $D(Y|X)$, the effective number of devices of type Y when X is taken into account is reduced by a factor $1/\Lambda$ because of the technology. The more significant the technology, the greater the reduction and the larger Λ. This will be our key marker in subsequent analysis. Unfortunately, in practice we rarely know $D(Y)$ and we use

$$\Lambda(X;Y)_{max} = D(Y)_{max}/D(Y|X) \geq 1 \tag{7}$$

as a proxy for technological importance where $D(Y)_{max} = n$, the number of variants of Y. Despite its appearance in Eq. (6) $\Lambda(X, Y)$ is symmetric $\Lambda(X, Y) = \Lambda(Y, X)$; $\Lambda(X;Y)_{max}$ is not, but it still a useful guide for technological importance. To go further requires that we consider multi-conditional entropies H(X|Y,Z) and beyond. Conditional frequencies p(x|y,z) = p(x,y,z)/p(y,z) satisfy $\sum_{x \in X} p(x|y, z) = 1$ and it is crucial to preserve this in our calculations. It can be shown that, if $\Lambda(X, Y, Z)$ is the exponential of the mutual (interaction) information, then

$$\Lambda(X, Y, Z) \geq \Lambda(X, Y)\Lambda(Y, Z)\Lambda(Z, X) \tag{8}$$

This is a demonstration of synergy, that for compound technologies implemented simultaneously or sequentially, the whole effect is greater than that of the parts.

Synergy plays an important role in comparing technologies (Rajpal & Guerrero, 2023; Williams & Beer, 2010) where it is suggested that high synergy scores (e.g., the ratio of the two sides of Eq. 8) quantify technological sophistication. However, to exploit this requires better data than ours and, in the absence of such data, Eq. (8) is not valid for our $\Lambda(X;Y)_{max}$. However, we would not be surprised if, in terms of dominant features,

$$\Lambda(X;Y;Z)_{max} \sim \Lambda(X;Y)_{max}\Lambda(Y;Z)_{max}\Lambda(Z;X)_{max}. \tag{9}$$

We stress that the right-hand sides of Eqs. (8) and (9) only differ by a numerical factor and not a functional term. However, what this analysis does do is to cement $\Lambda(X, Y)$ as the natural measure of technological significance.

The relative technological complexity may be expressed as the ratio of joint diversity of the technology's modification D_m to the product of equally distributed variations in all component parts used in the arrangement of this technology. This ratio represents the exponentiated [joint] evenness well known in archaeological research on diversity (Shott, 1989, 2010; Wiśniewski et al., 2022). Therefore, given all other factors being equal, the first approximation of our research hypothesis may be expressed as the inverse of the joint exponentiated evenness:

$$\delta = \frac{\prod k_i}{D_m}, \delta > 1 \tag{10}$$

where k is the number of variations in ith component part of the technology, and δ is the convergence score. The higher the convergence score (which values in comparative context), the more likely are modifications of the technology invented independently.

The Cucuteni-Tripolye Pottery Kilns: Technological Complexity and Archaeological Analogies (a Case Study)

As we have argued, the values of joint entropy or diversity reflect the likelihood for convergent evolution in a comparative context. The increase in joint information and decrease in diversity indicates an increase in the likelihood of convergence and vice versa. Let us demonstrate the utility of this approach to help explain real archaeological data.

The following section addresses the complexity of pottery kilns and likelihood of their convergent evolution. Being composed of interconnected component parts with their specific functions, pottery kilns represent a good example of complex technology in transforming natural phenomena for human purposes. Our case study takes an example of double-chamber pottery kilns from the settlements belonging to the Cucuteni-Tripolye cultural complex (CTCC) in Chalcolithic Southeastern Europe. Meanwhile, this section sequentially introduces the cultural complex and its pottery kilns, analyses variability of their sequentially linked components, and discusses kilns' complexity and the convergent evolution of similar features in an extended spatio-chronological framework.

Data Input

The CTCC was spread from the Carpathians to the eastern bank of Dnieper in modern Romania, Moldova and Ukraine from c. 5000 to 3000/2950 BC (Fig. 1). The largest settlements of the cultural complex, more specifically its Tripolye component (the so-called “giant-settlements” or “mega-sites”), reached a size of 100–340 ha. Settlement clusters are characterized by well-developed site-size hierarchies.

The CTCC is taxonomically subdivided into archaeological cultures. The transition from the earliest, Precucuteni culture, to the subsequent Ariușd, Cucuteni, Eastern Tripolye culture (hereinafter – ETC) and Western Tripolye culture (hereinafter – WTC) is manifested by the significant transformation of pottery styles. Earlier, Precucuteni ceramics was characterized by incised and fluted decoration. A small percentage of vessels were painted before firing (e.g., Dumitrescu, 1963). Later, Cucuteni and WTC pottery was painted before firing; though, the combination of the incisions and painting in a small percentage is also known (Dumitrescu, 1963; Ryzhov, 2021). ETC ceramics generally continues the tradition of incised and fluted decoration. However, pottery assemblages of the ETC sites include up to 20–40% of vessels painted before firing. A combination of painted ornamentation with incised and fluted decoration has been observed (Tsvek, 2006).

The significant amount of high-quality painted pottery distinguishes the CTCC from the vast majority of other prehistoric cultural units, which were spread to the east of the Carpathians. Therefore, it is not surprising that the technological and socio-economic organization of CTCC ceramic production has been actively

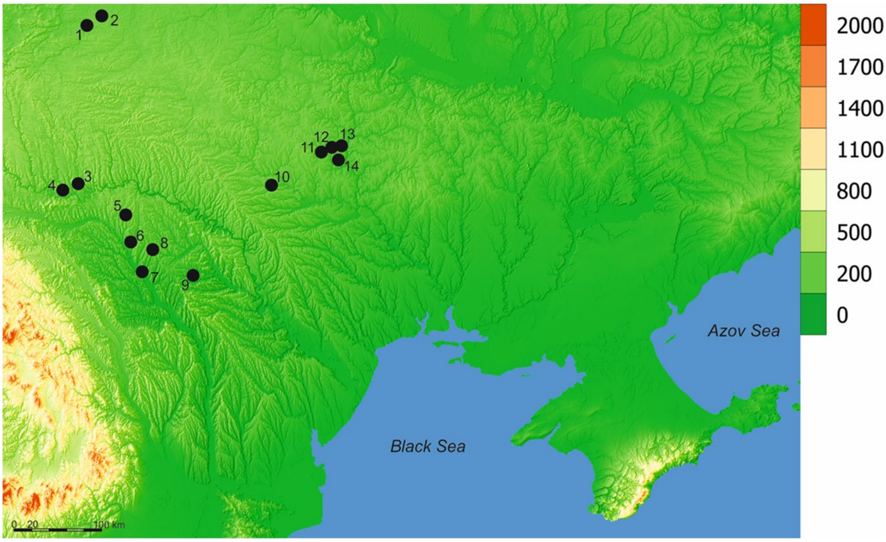

Fig. 1 Double-chamber pottery kilns of the Cucuteni-Tripolye cultural complex 1 – Novomalin-Podobanka, 2 – Ostrog-Zeman, 3 – Kamenets-Podolskiy – Tatarysky, 4 – Zhvanets, 5 – Trinca-Izvorul lui Luca, 6 – Hancăuţi I, 7 – Stolniceni, 8 – Costeşti 9, 9 – Chirileni III, 10 – Trostyanchik, 11 – Dobrovody, 12 – Talianki, 13 – Maidanetske, 14 – Nebelevka

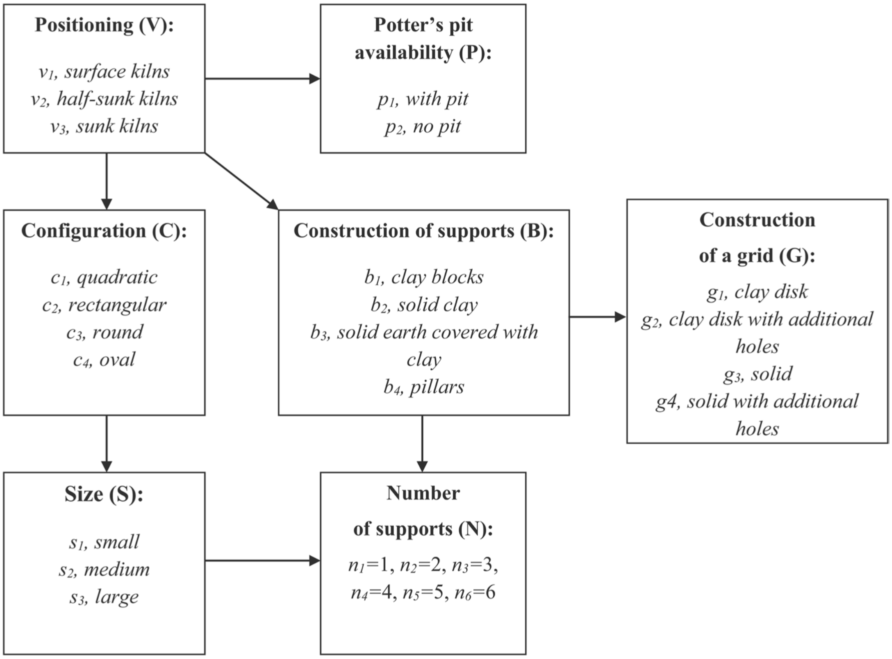

Fig. 2 Kiln technology: *Chaîne opératoire* of the double-chamber pottery kilns construction and usage. Rectangles demonstrate the component parts and their variations, and arrows indicate operation chain in the construction and usage of kilns starting from their positioning in relation to the surface and ending up by construction of a grid. A detailed list of partitioning features is given in Table 1

discussed for decades. For instance, the hypothetical functioning of pottery centres in providing neighbouring settlements with their products has been questioned since the 1920s (Movsha, 1971), while assumptions on pottery making in the large settlements and its further distribution to settlement clusters has contributed to the interpretation of mega-sites for proto-cities (e.g., Videiko, 2002). However, most recent geophysical surveys and excavations have indicated pottery kilns at numerous settlements of both small and large size, including some (but not all) small settlements in the surroundings of mega-sites, suggesting that ceramic production was already in place (Ohlrau, 2022; Ohlrau & Rud, 2019). The relationship of these features to the division of labour is being considered (Ellis, 1984; Korvin-Piotrovskiy et al., 2016; Ţerna et al., 2019b).

Consider *double-chamber kilns* which have the best quantitative representation (exceeding 30 devices) among the several types of CTCC pottery kilns (Ryzhov, 2002; Tencariu, 2010; Tsvek, 1994). A number of features of this type are known from older excavations (e.g., Bicbaev, 1990; Movsha, 1971). Recent geophysical surveys followed by the excavations of the WTC settlements Nebelevka, Stolniceni, Dobrovody, Talianki, Maidanetske has significantly extended our knowledge of the variability of such kilns. A database of double-chamber kilns has been presented by Ţerna and co-authors (2017). New evidence from Kamenets-Podolskiy – Tatarysky and Trostiancnyk in modern Ukraine contributes to the database with the archaic features of this type (Diachenko & Sobkowiak-Tabaka, 2020; Rud et al., 2019). Recently published data on kilns from Ostrog, Ukraine and Stolniceni, Republic of Moldova (Pozikhovskyj, 2019; Ţerna et al., 2019a; 2019b) and experimental research (Manea et al., 2022; Tencariu et al., 2021) extend our knowledge further on the internal variability of the analysed devices.

The CTCC Double-Chamber Pottery Kilns as Variable Components' Arrangement

The CTCC double-chamber pottery kilns consisted of a combustion chamber used for burning firewood and a firing chamber used for firing vessels. The chambers were separated by a platform placed on supports or pillars in the combustion chamber. Supports subdivided the area of the combustion chamber into so-called "channels." Hot air from the combustion chamber was passed to the firing chamber through the holes in a platform.

Several classification schemes exist, based on variations in some of their components (e.g., Diachenko & Sobkowiak-Tabaka, 2020; Korvin-Piotrovskiy & Ovchinnikov, 2020; Ţerna et al., 2019b). As an alternative to this common taxonomist approach, our case study considers double-chamber kilns through the *chaîne opératoire* of the kiln's construction sequences (Bicbaev, 1990; Sîrbu & Bicbaev, 2017; Ţerna et al., 2019b). We focus on the connectedness limiting the variability of components (Fig. 2).

Double-chamber pottery kilns were constructed on the surface (Fig. 3) or sunken into the ground either to the depth of their combustion chambers (Fig. 4), or completely or partially sunken to the depth of their firing chambers (Fig. 5). Kiln effectiveness, *i.e.*, procuring high temperatures for a longer duration, is at its lowest for surface kilns, increasing as the kilns are completely or partially sunken into the ground to the depth of the firing chamber (Bobrinskij, 1991). For the convenience of usage surface kilns and kilns sunken into the ground to the depth of the combustion chamber may have been or may have not been accompanied by a potter's pit. A potter's pit or the use of differences in landscape elevation was required for those devices with a completely or partially sunken firing chamber.

Kilns constructed on the surface or sunken into the ground to the depth of combustion chamber had a footprint that was quadratic with rounded corners, rectangular with rounded corners, circular or an oval shape. The configuration of the kilns with partially or completely sunken firing chambers was limited to being rectangular (with rounded corners), circular or oval. These features determined their size. More specifically, quadratic and rectangular-shaped kilns could have small (up to 1.6 m^2), medium (2.1–3.5 m^2) and large size (4.4–6.4 m^2), while circular and oval-shaped features were only of a small or medium size.

Platforms in kilns either constructed on the surface or sunken into the ground to the depth of their combustion chambers were placed on supports (Figs. 3 and 4), while platforms in kilns partially or completely sunken into the ground were kept by supports or pillars (Fig. 5). Supports may be subdivided into three types by their construction techniques. These types include supports composed of distinct clay

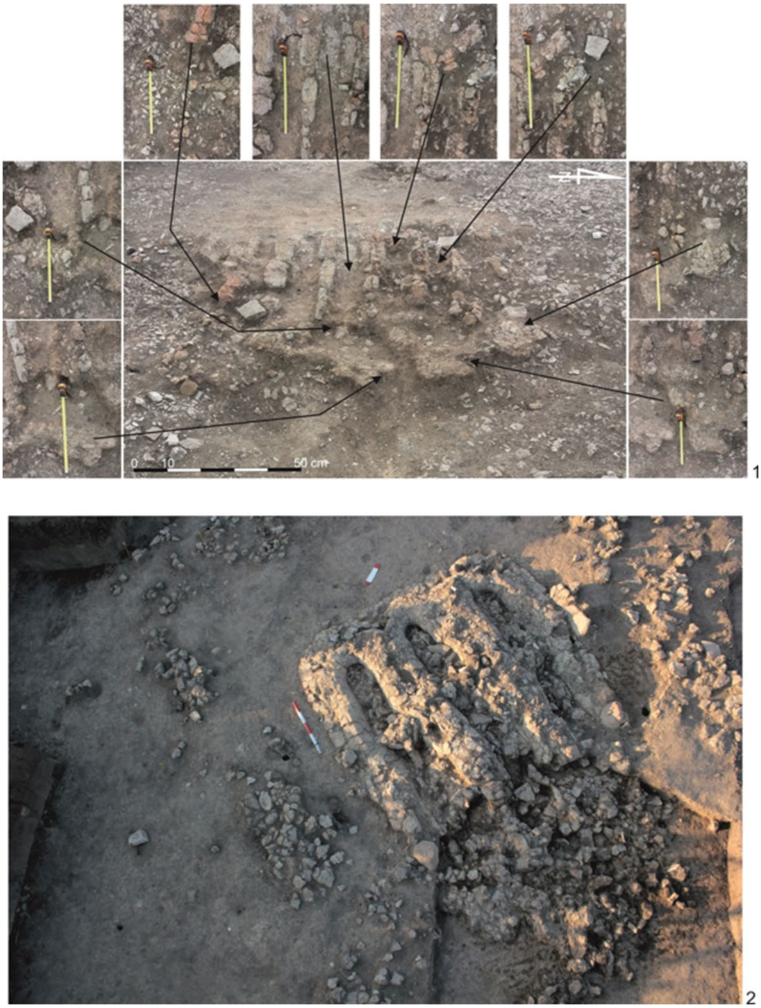

Fig. 3 Surface pottery kilns. 1 – Kamenets-Podolskiy – Tatarysky, 2 – Nebelevka (redrawn from: 1 - Diachenko & Sobkowiak-Tabaka, 2020: 157, Fig. 3 (1); 2 - Chapman et al., 2018: file 'Ind_adjacent_deposits.jpg' (2))

blocks, solid clay and solid earthen supports covered with clay. Obviously, supports of the latter type were constructed only in kilns which were sunken into the surface.

Since supports composed of distinct clay blocks were placed closer to each other than solid ones, construction techniques of supports together with kilns' size determined the number of supports. There was an important developmental trend of decreasing the number of supports in order to achieve a more even distribution of temperature in the combustion chamber (Videiko, 2019). This trend may be illustrated by the kiln from Maidanetske, which represents three construction phases (e.g., Korvin-Piotrovskiy et al., 2016; Ohlrau, 2020; Videiko,

Fig. 4 Half-sunk pottery kilns. 1 – Kamenets-Podolskiy – Tatarysky, 2 – Stolniceni (redrawn from: 1 - Diachenko & Sobkowiak-Tabaka, 2020: 162, Fig. 4; 2 - Ţerna et al., 2019b: 45, Fig. 4)

2019). The excavated large features constructed on the surface included six supports composed of clay blocks (Kiln 1 from Kamenets-Podolskiy – Tatarysky: Diachenko & Sobkowiak-Tabaka, 2020; see Fig. 2, a) or two–three solid clay supports (for example, Nebelevka: Fig. 3 B, Talianki: Burdo & Videiko, 2016, cf. Chapman & Gaydarska, 2016; Korvin-Piotrovskiy et al., 2016; Shatilo, 2021; Ostrog-Zeman: Pozikhovskyj, 2019). For the empirically known cases we find one – three supports composed of clay blocks or one – two solid clay supports in small surface kilns. The same features for medium size kilns suggest two – four supports composed of clay blocks or one – three solid supports, while kilns of a large size, most likely included three – six supports composed of clay blocks or two – four solid supports.

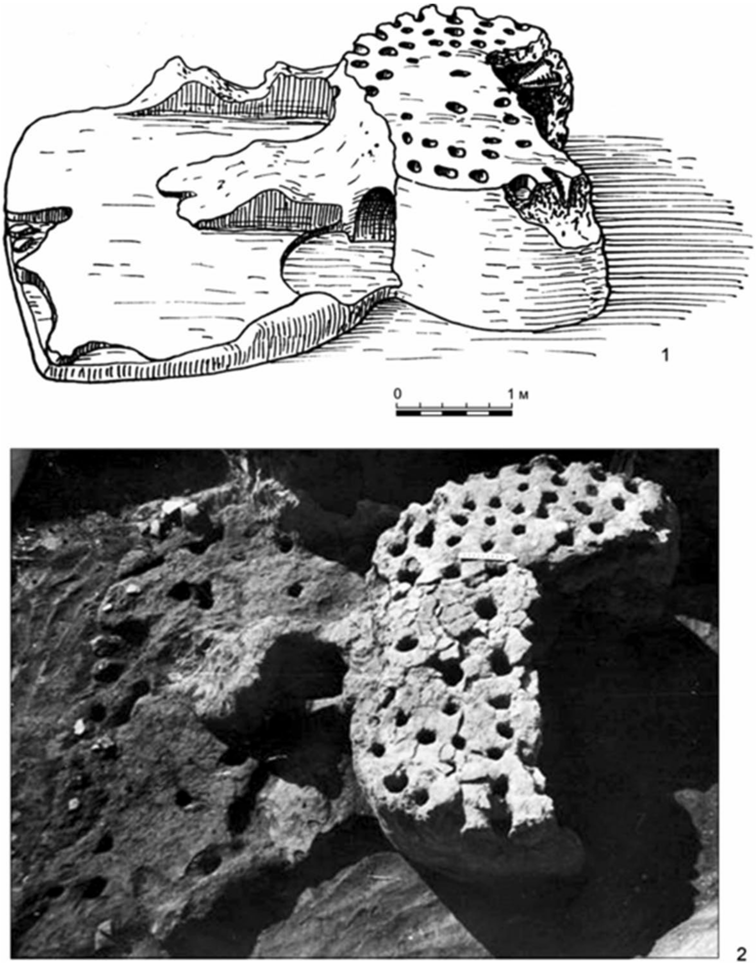

Fig. 5 Sunk pottery kiln from Costeşti 9: field drawing and photo (redrawn from Sîrbu & Bicbaev, 2017: 334, Fig. 2)

Among the kilns with combustion chambers sunken into the ground with firing chambers placed at surface level, there are empirically known cases of small features with a single support composed of clay blocks (for example, see Kiln 2 from Kamenets-Podolskiy – Tatarysky: Diachenko & Sobkowiak-Tabaka, 2020; see Fig. 4, a). Medium and large features with a single solid earthen support covered with clay are also known empirically (for example, kilns from Stolniceni: Ţerna et al., 2017; 2019a; 2019b; see Fig. 4, b). However, we may also assume usage of one-two supports composed of clay blocks or two solid clay supports in medium-sized kilns sunken into the ground to the depth of the combustion chamber. All kilns with firing chambers sunken into the ground have a single earthen support covered with clay (for example, features from Costeşti 9: see Fig. 5 and Trinca-Izvorul lui

Luca: Bicbaev, 1990; Sîrbu, 2015; Sîrbu & Bicbaev, 2017) or one-two pillars keeping a platform (for example, a number of devices from Zhvanets: Movsha, 1971).

The construction techniques of the supports determined the construction of the platform, which could be solid or composed of disks (Fig. 3). Fragments of such disks made of clay with organic admixtures were found near the kilns (for example, Nebelevka and Maidanetske: Burdo & Videiko, 2016; Korvin-Piotrovskiy et al., 2016; Ohlrau, 2020), on top of supports inside these features (Kamenets-Podolskiy – Tatarysky: Diachenko & Sobkowiak-Tabaka, 2020), or inside combustion chambers. The most notable example of the latter comes from Stolniceni, where the archaeologically complete disk was explored inside the channel (Ţerna et al., 2017; see Fig. 4, b). Supports composed of clay blocks could be covered only by clay discs, while either clay disks or solid platform could be placed on solid supports.

Holes in a platform were located in rows above "channels" (surface kilns and features with combustion chamber sunken into the ground and firing chamber at the surface level; for example, Kiln A in Talianki: Korvin-Piotrovskiy et al., 2016) or shaped nearly concentric structures (kilns with firing chamber partially or completely sunken into the ground; for example, the device from Costeşti 9: Sîrbu & Bicbaev, 2017; see Fig. 5). A number of surface kilns and features with firing chamber at the surface level, which had solid platforms or platforms composed of clay disks, included additional holes in supports and, respectively, platforms, as well as holes in thick walls of these kilns (Ţerna et al., 2019b). The additional holes represent the technological solution enabling more even distribution of hot air in firing chamber. Therefore, following S. Ţerna and co-authors (2019b) we consider addition of such holes to solid platforms and platforms composed of clay discs for a distinct technological solution in the platforms' construction.

The Entropy and Diversity of Limited Solutions (Maximal Equivocation)

This analysis of the technological design structure is the basis for our estimation of the internal complexity of the technology design of Fig. 2, which shows kiln labels V, P, C, etc. together with their connectivity through technological development. The details of what follows can be found in Table 1. In the first column of Table 1 we show the features which partition each label (reproduced below).

- Kiln positioning V: v_1, surface kilns; v_2, half-sunk kilns; v_3, sunk kilns.
- Pit availability P: p_1, with pit; p_2, no pit.
- Configuration C: c_1, quadratic; c_2, rectangular; c_3, round; c_4, oval.
- Construction of supports B: b_1, clay blocks; b_2, solid clay; b_3, solid earth covered with clay; b_4, pillars.
- Size S: s_1, small; s_2, medium; s_3, large.
- Number of supports N: $n_1 = 1; n_2 = 2; n_3 = 3; n_4 = 4; n_5 = 5; n_6 = 6$.
- Construction of grid G: g_1, clay disks; g_2, clay disks with additional holes; g_3, solid; g_4, solid with additional holes.

Table 1 Modelling kiln entropies

Building block	Variations	Conditional probabilities	Conditional entropy
A: Surface kilns			
Vertical relation to surface	v_1, surface kilns	$p(v_1)$	$H = -p(v_1)\ln p(v_1)$
Potter's pit availability	p_1, with pit p_2, without pit	$p(p_1 \mid v_1) = p(p_2 \mid v_1) = 1/2$	$H(P \mid v_1) = p(v_1)\ln 2$
Configuration	c_1, quadratic c_2, rectangular c_3, round c_4, oval	$p(c_1 \mid v_1) = p(c_2 \mid v_1) = p(c_3 \mid v_1) = p(c_4 \mid v_1) = 1/4$	$H(C \mid v_1) = 2p(v_1)\ln 2$
Construction of supports	b_1, clay blocks b_2, solid clay b_3, solid earth covered with clay b_4, pillars	$p(b_1 \mid v_1) = p(b_2 \mid v_1) = 1/2$	$H(B \mid v_1) = p(v_1)\ln 2$
Size	s_1, small s_2, medium s_3, large	$p(s_1 \mid c_1, v_1) = p(s_2 \mid c_1, v_1) = p(s_3 \mid c_1, v_1) = 1/3$ $p(s_1 \mid c_2, v_1) = p(s_2 \mid c_2, v_1) = p(s_3 \mid c_2, v_1) = 1/3$ $p(s_1 \mid c_3, v_1) = p(s_2 \mid c_3, v_1) = p(s_1 \mid c_4, v_1) = p(s_2 \mid c_4, v_1) = 1/2$	$H(S \mid C, v_1) = (p(c_1, v_1) + p(c_2, v_1))\ln 3 + (p(c_3, v_1) + p(c_4, v_1))\ln 2$
Number of supports	$n_1 = 1$ $n_2 = 2$ $n_3 = 3$ $n_4 = 4$ $n_5 = 5$ $n_6 = 6$	$p(n_1 \mid s_1, b_1, v_1) = p(n_2 \mid s_1, b_1, v_1) = p(n_3 \mid s_1, b_1, v_1) = 1/3$ $p(n_1 \mid s_1, b_2, v_1) = p(n_2 \mid s_1, b_2, v_1) = 1/2$ $p(n_2 \mid s_2, b_1, v_1) = p(n_3 \mid s_2, b_1, v_1) = p(n_4 \mid s_2, b_1, v_1) = 1/3$ $p(n_1 \mid s_2, b_2, v_1) = p(n_2 \mid s_2, b_2, v_1) = p(n_3 \mid s_2, b_2, v_1) = 1/3$ $p(n_3 \mid s_3, b_1, v_1) = p(n_4 \mid s_3, b_1, v_1) = p(n_5 \mid s_3, b_1, v_1) = p(n_6 \mid s_3, b_1, v_1) = 1/4$ $p(n_2 \mid s_3, b_2, v_1) = p(n_3 \mid s_3, b_2, v_1) = p(n_4 \mid s_3, b_2, v_1) = 1/3$	*No obvious simplification*
Construction of a grid	g_1, clay discs g_2, clay discs with additional holes g_3, solid grid g_4, solid grid with additional holes	$p(g_1 \mid b_1, v_1) = p(g_2 \mid b_1, v_1) = 1/2$ $p(g_1 \mid b_2, v_1) = p(g_2 \mid b_2, v_1) = p(g_3 \mid b_2, v_1) = p(g_4 \mid b_2, v_1) = 1/4$	$H(G \mid B, v_1) = (p(b_1, v_1) + 2p(b_2, v_1))\ln 2$

Table 1 (continued)

Building block	Variations	Conditional probabilities	Conditional entropy
B: Half-sunk kilns			
Building block	Variations	Conditional probabilities	Conditional entropy
Vertical relation to surface	v_2, half-sunk kilns	$p(v_2)$	$H = -p(v_2)\ln p(v_2)$
Potter's pit availability	p_1, with pit p_2, without pit	$p(p_1\|v_2) = p(p_2\|v_2) = 1/2$	$H(P\|v_2) = p(v_2)\ln 2$
Configuration	c_1, quadratic c_2, rectangular c_3, round c_4, oval	$p(c_1\|v_2) = p(c_2\|v_2) = p(c_3\|v_2) = p(c_4\|v_2) = 1/4$	$H(C\|v_2) = 2p(v_2)\ln 2$
Construction of supports	b_1, clay blocks b_2, solid clay b_3, solid earth covered with clay b_4, pillars	$p(b_1\|v_2) = p(b_2\|v_2) = p(b_3\|v_2) = 1/3$	$H(B\|v_2) = p(v_2)\ln 3$
Size	s_1, small s_2, medium s_3, large	$p(s_1\|c_1, v_2) = p(s_2\|c_1, v_2) = p(s_3\|c_1, v_2) = 1/3$ $p(s_1\|c_2, v_2) = p(s_2\|c_2, v_2) = p(s_3\|c_2, v_2) = 1/3$ $p(s_1\|c_3, v_2) = p(s_2\|c_3, v_2) = p(s_1\|c_4, v_2) = p(s_2\|c_4, v_2) = 1/2$	$H(S\|C, v_2) = (p(c_1, v_2) + p(c_2, v_2))\ln 3 + (p(c_3, v_2) + p(c_4, v_2))\ln 2$
Number of supports	$n_1 = 1$ $n_2 = 2$ $n_3 = 3$ $n_4 = 4$ $n_5 = 5$ $n_6 = 6$	$p(n_1\|s_1, b_1, v_2) = p(n_1\|s_1, b_2, v_2) = p(n_1\|s_2, b_3, v_2) = p(n_1\|s_3, b_3, v_2) = 1$ $p(n_1\|s_2, b_1, v_2) = p(n_2\|s_2, b_1, v_2) = p(n_1\|s_2, b_2, v_2) = p(n_2\|s_2, b_2, v_2) = 1/2$	$H(N\|S, B, v_1) = (p(S, b_1) + p(S, b_2))\ln 2$
Construction of a grid	g_1, clay discs g_2, clay discs with additional holes g_3, solid grid g_4, solid grid with additional holes	$p(g_1\|b_1, v_2) = p(g_2\|b_1, v_2) = 1/2$ $p(g_1\|b_2, v_2) = p(g_2\|b_2, v_2) = p(g_3\|b_2, v_2) = p(g_4\|b_2, v_2) = 1/4$ $p(g_1\|b_3, v_2) = p(g_2\|b_3, v_2) = p(g_3\|b_3, v_2) = p(g_4\|b_3, v_2) = 1/4$	$H(G\|B, v_2) = (p(b_1, v_2) + 2p(b_2, v_2) + 2p(b_3, v_2))\ln 2$

Table 1 (continued)

Building block	Variations	Conditional probabilities	Conditional entropy
C: Sunken kilns			
Building block	Variations	Conditional probabilities	Conditional entropy
Vertical relation to surface	v_3, sunk kilns	$p(v_3)$	$H = -p(v_3)\ln p(v_3)$
Potter's pit availability	p_1, with pit p_2, without pit	$p(p_1 \mid v_3) = 1$	$H(P \mid v_3) = 0$
Configuration	c_1, quadratic c_2, rectangular c_3, round c_4, oval	$p(c_2 \mid v_3) = p(c_3 \mid v_3) = p(c_4 \mid v_3) = 1/3$	$H(C \mid v_3) = p(v_3)\ln 3$
Construction of supports	b_1, clay blocks b_2, solid clay b_3, solid earth covered with clay b_4, pillars	$p(b_1 \mid v_2) = p(b_2 \mid v_2) = p(b_3 \mid v_2) = 1/3$	$H(B \mid v_3) = p(v_3)\ln 3$
Size	s_1, small s_2, medium s_3, large	$p(s_1 \mid c_2, v_3) = p(s_2 \mid c_2, v_3) = p(s_3 \mid c_2, v_3) = 1/3$ $p(s_1 \mid c_3, v_3) = p(s_2 \mid c_3, v_3) = p(s_1 \mid c_4, v_3) = p(s_2 \mid c_4, v_3) = 1/2$	$H(S \mid C, v_2) = (p(c_2, v_3))\ln 3 + (p(c_3, v_3) + p(c_4, v_3))\ln 2$
Number of supports	$n_1 = 1$ $n_2 = 2$ $n_3 = 3$ $n_4 = 4$ $n_5 = 5$ $n_6 = 6$	$p(n_1 \mid s_1, b_3, v_3) = p(n_1 \mid s_1, b_4, v_3) = p(n_1 \mid s_2, b_3, v_3) = p(n_1 \mid s_2, b_4, v_3) = p(n_1 \mid s_3, b_3, v_3) = 1$ $p(n_1 \mid s_3, b_4, v_3) = p(n_2 \mid s_3, b_4, v_3) = 1/2$	$H(N \mid S, B, v_3) = \ln 2p(s_1, b_4, v_3)$
Construction of a grid	g_1, clay discs g_2, clay discs with additional holes g_3, solid grid g_4, solid grid with additional holes	$p(g_4 \mid b_3, v_3) = p(g_4 \mid b_4, v_3) = 1$	$H(G \mid B, v_2) = 0$

Arguably, it is easier to estimate conditional frequencies than joint frequencies. In the absence of reliable statistical data on the kilns, whose state of preservation is poor, we fall back onto "Laplace's Principle of Indifference" (Keynes, 1921: 41–64) or the Principle of Maximum Ignorance or "epistemic modesty" (Jaynes, 1973, 1979). In the language of Eq. (1) we look for the "least surprising" outcome that could encode the prior data (which coincidently, is also the most likely outcome) by maximising conditional Shannon information. Such conditional entropies are termed "equivocations" (Hellman et al., 1970). Our assumption of *maximal equivocation* gives equal probabilities in the rows of the third column of Table 1, the Hartley function (Hartley, 1928). Alan Wilson has termed this overall approach a super-principle (Wilson, 2010). Any probabilities not included are set to zero (uncorrelated). Although wrong in detail such "naïve" choices, which are ignorant to cost–benefit decision making and the long-term social learning, are informed by the limited data that we possess.

At each stage we implement the constraints of Eq. 5. In the third column of Table 1 we give the conditional entropies subject to these constraints. From these we get a general feeling as to which features have an impact. To see how the analysis works, we begin with the simplest technological couplings between kiln construction V and support construction B, pit accessibility P and configuration C (see Fig. 2). Equation 6 is the key equation that relates technological impact to the mutual information between systems and their variants.

The joint entropy of surface, half-sunk and sunken kilns is estimated at, respectively, c. 4.96, 4.63 and 2.74 (Eq. 2). Corresponded values of joint diversity are, respectively, 142.82, 102.75 and 15.42. The convergence scores estimated with the Eq. 10 (surface kilns: c. 48.4; half-sunk kilns: c. 67.3, sunk kilns: c. 448.3) show that the likelihood of independent invention of sunk kilns in all their variability c. 9 and 6 times exceed the related values obtained for respectively, surface and half-sunk kilns. Half-sunk kilns are c. 1.4 more likely to be invented independently than the surface kilns in all their variability.

The 'technological importance' in our simplified version of $\Lambda(X;Y)_{max}$ takes its minimal value of 1 for the pit availability, kilns configuration and supports construction in case of all three groups of the analysed features. The value of $\Lambda(X;Y)_{max}$ obtained for the kilns size of sunken features (c. 1.31) somewhat exceeds the related values obtained for surface and half-sunk kilns (c. 1.22 in both cases). The 'technological importance' of the supports number is distributed as follows: c. 2.33 for surface kilns, c. 1.82 for half-sunk devices, and c. 1.78 for sunken kilns. Finally, the values of $\Lambda(X;Y)_{max}$ obtained for the grid construction are as follows: c. 1.41 in case of surface kilns, c. 1.26 in case of half-sunk devices and 1 in case of half-sunk kilns.

Sometimes the details can obscure the fact that the technological impact $\Lambda(X;Y)_{max}$ of Eq. 7 is driven by very few factors. Most simply, on aggregating the joint entropies above, Pit accessibility and configuration, as conditioned by kiln construction only depend on $p\left(v_3\right)$ as

$$\Lambda(V;P)_{max} = 2^{p\left(v_3\right)} \text{ and } \Lambda(V;C)_{max} = (4/3)^{p\left(v_3\right)} \tag{11}$$

From Eq. (8) we would make the reasonable guess, since the right-hand sides of (8) and (9) only differ by numerical factors, and that P and C show no mutual information, that

$$\Lambda(V;P;C)_{max} \sim a^{p\left(v_3\right)} \tag{12}$$

or greater, for some factor a. What matters is that the technological impact factor increases with the implementation of sunken kilns.

A similar, but less dramatic effect on sinking kilns occurs when considering how size is conditioned by both configuration and kiln construction, for which $\Lambda(S;C;V)_{max} = (3/2)^q 3^p$, where $q = p\left(c_3\right) + p\left(c_4\right)$ and $p = (1/3)p\left(v_3\right)$, maximised when q = 1 *i.e.*round or oval configurations for sunken kilns with p = 1/3, $i.e. p\left(v_3\right) = 1$, as is the case (see the "Results" section).

The situation is somewhat similar for grid construction as conditioned by support construction and kiln construction. The impact factor reflects this as

$$\Lambda(G;B;V)_{max} \sim 2^{2-a+p} \tag{13}$$

where $p = (1/3)p\left(v_3\right)$ as before, and $a = p\left(b_1\right) + 2p\left(b_2\right)$. We see that high technological impact requires that B is dominated by support types b_3 and b_4 i.e. earth covered with clay and pillars and sunken kilns, again as is the case (see the "Results" section).

It is more difficult to reach any firm conclusions for $\Lambda(N;S;B;V)_{max}$ but there are many circumstances in which the technology factor is amplified by sunken kilns.

Results

As stated by the research hypothesis, the probability of convergence increases with the decrease of technological complexity. Therefore, the obtained results presume a higher probability of half-sunk kilns comparing to surface features. Sunken kilns have the highest probability of convergence in different populations among the three analysed groups of kilns.

As we have seen above, model expectations generally fit the empirical observations while suggesting a certain extent of the diffusion of the devices with sunken combustion chamber. Certain variations of the surface kilns and features with sunken combustion chamber have similarities and analogies in, respectively, Late Minoan Crete (Shaw et al., 2001), Neolithic Southeastern Europe (Minichreiter, 1992, 2001, 2007; Tencariu, 2010), Chalcolithic Iraqi Kurdistan (Squitieri et al., 2022) and Greek and Roman time and ethnographic Eastern Europe (Bobrinskij, 1991). However, such features are much less known archaeologically than the kilns with completely or partly sunken firing chamber of a simple design structure having analogies and similarities in Greek and Roman cities, Roman time *Barbaricum*, and also Medieval cities and modern time villages all over Europe (e.g., Bobrinskij, 1991).

In quantitative terms the aforementioned similarities and analogies mean nearly equal values of internal diversity and convergence scores. Let us illustrate this by the example of the Roman time Cherniakhovskaya culture kilns, whose spatial extent majorly overlaps and even extends the CTCC area. According to Bobrinskij's (1991) data scaled to the resolution of this study, half-sunk and sunken features of Cherniakhovskaya culture are similar in structure. They differ from the CTCC kilns by the support construction (no support, support, or pillar) and number (zero in case of no support and one in case of support or pillar). Given this simplified description of the design, the internal diversity of Cherniakhovskaya culture kilns is estimated at the considerably low value of 20.6 indicating the high likelihood of convergence. Recent evidence confirms independent development of Chernikhovskaya culture sunken features with pillars (Petrauskas et al., 2017) earlier associated with diffusion from the Danubian provinces of the Roman Empire (e.g., Bobrinskij, 1991). Convergent evolution of kilns characterized by simple design structure and, therefore, 'lower' internal diversity and 'higher' technological significance is also confirmed by the Medieval data (Teslenko & Myronenko, 2022). Thus, our estimations surprisingly find that broad distribution of sunken pottery kilns, may be the consequence of their relatively low internal complexity rather than higher efficiency.

The example of Cucuteni-Tripolye kilns illustrates that independent development or transmission does not necessarily go about complex technology as a whole. Decisions resulting in "technological importance" of connecting component parts are crucial (Eqs. 5–7). The constraints on conditional frequencies of Table 1 still leave the fundamental frequencies and many joint frequencies undetermined. As we have noted, what is striking about Eqs. 5–7 applied to Cucuteni-Tripolye pottery kilns is that the "most likely" outcomes or the bounds on technological significance Λ depend on so few independent frequencies. That is, many of the details in developing kiln technology do not matter in determining Λ. In fact, the dominant feature for developing kiln technology (in the sense of reducing diversity) is the sinking of kilns, from which so many other benefits in diversity reduction flow.

It should be noted that our current knowledge on the chronological distribution of the CTCC pottery kilns suggests the overlap in usage of surface and half-sunk features later followed by their replacement by sunken kilns (Diachenko & Sobkowiak-Tabaka, 2020; Ţerna et al., 2019b; chronology of sites follows Harper et al., 2021). With $p\left(v_3\right)$ increasing over time we can make the more active statement, for these features, that the increase in the formation of pit kilns goes hand in hand with a greater technological simplification (reduction of diversity). The presence of pit kilns also plays a role in the impact of configurations C on size S, although the dominant reduction in diversity is determined by the presence of round and oval kilns, correlated to kiln type. By the time we are looking at the effects of the system on grid construction G, we still retain some memory of kiln type, the reduced diversity of grid construction now more conditioned by the frequency of clay and clay block support of the grid platforms.

Thus, different communities can differ in kiln construction details but, as long as they sink their kilns, they will achieve roughly the same outcome of maximum diversity reduction, particularly if the kilns are round or oval with a preference for solid clay supports. Our example is very idealised in assuming maximal equivocation, but this is what we understand by convergent evolution, which proceeds by getting the key factors right (out of many), permitting many ways to achieve the results, as one would expect from different communities.

It could be argued that we are getting out no more than we are putting in, *ceteris paribus*. However, the merit of our approach is that we did not know what we were putting in and now, to some extent, we do.

Conclusion and Discussion

The idea of diffusion of complex technologies is deeply rooted in the way archaeology manages its data. Spatio-chronological distribution of features referred to a certain "type" with its multiple definitive criteria and replacement of these types creates an impression of innovations as single-act events. Of course, innovation flow with migrating populations (demic diffusion) or knowledge exchange (cultural diffusion), are evident and well-studied. For instance, the latter may be exemplified by the diffusion of the potters' wheel in the Near East (Roux, 2014). Moreover, the idea of a certain degree of a specific technologies' complexity after which this technology is less likely to be invented by a single individual is generally agreed among the experts in modern and ancient technologies (Arthur, 2009; Johnson, 2010; Mesoudi, 2011b; Roux, 2010; Shennan, 2013; Strumsky & Lobo, 2015). However, cultural and demic diffusion do not explain the whole range of archaeological data. Convergent evolution may occur as the result of functional, economic or development constraints, and during the million years of human existence it was a recurring phenomenon (Carbonneau, 2018; Clarkson et al., 2018; Eren et al., 2018). Analysis of the *chaîne opératoire* in flint processing finds that convergence results from the limited number of possible solutions for processing techniques or tool types (McGhee, 2011, 2018). Therefore, it is no surprise that empirical evidence on the convergent evolution of stone tools is growing (e.g., Clarkson et al., 2018; Derevianko, 2010; Kozłowski, 2015; Kuhn & Zwyns, 2018; Snyder et al., 2022).

Providing the measures of complexity and connectivity in technologies, our study shows that in numerous cases technological evolution has to be scaled to the 'technologically important' (in quantitative terms) component parts, which introduction shapes a ground for extinction and self-evolvement caused by the cascade effects along technological design structure (Schiffer, 2005). This leads to the conclusion of significantly underestimated convergence in archaeological research. Similar purposes, availability of the component parts in a culture, and specific connectedness of these component parts may result in the independent innovation and development of a technology. Similar technological solutions in the technologically important component parts and technological design structure (to which we provide a quantitative measure) define the spread of similar devices in various locations. Surprisingly, such a broad distribution may result from relatively low internal diversity rather than from higher efficiency.

The reader should be aware that the approach presented here for quantifying technological complexity and likelihood of convergence presumes the impact of all other factors being equal, the most likely of all possible outcomes in the absence of further information. While providing a good null model, different populations adopt innovations in various ways due to their size and structure, cognitive and behavioural complexity, differences in learning process, certain degree of resistance to novelties, variation and selection biases, production costs and benefits (Bentley & O'Brien, 2017; Bentley et al., 2011; Boyd & Richerson, 1985; Boyd et al., 2013; Coolidge et al., 2016; de Groot & Bloxam, 2022; Deffner & Kandler, 2019; Knappett, 2016; Knappett & van der Leeuw, 2014; Lombard & Haidle, 2012; Mesoudi et al., 2013; Prentiss et al., 2022; Richerson & Boyd, 2005; Roux et al., 2017; Roux, 2010, 2014; Shennan, 2013). These factors have to be considered in further development and application of the proposed approach.

As technologies are scaled to their component parts which also might have been the subject of diffusion, convergent evolution, demic or cultural diffusion of technological innovations alone are rarely the plausible explanations in general contexts. These explanatory approaches require a proper balance when integrated into archaeological theory (Derevianko, 2010; Kozłowski, 2015; Kuhn & Zwyns, 2018). Nonetheless, future modifications to our quantitative approach would most increase the importance of currently neglected convergence in our understanding of the complex prehistoric past. Also, modifications to the method will allow its further applications to the evolution of social structures.

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Declarations

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