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Potter's Signal in Ceramic Vessel Forms: A Pairwise Morphometric Approach

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Research Article

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Abstract

This article addresses a long-standing issue in archaeological analysis: how to identify vessels made within the same production unit on the basis of form alone. It proposes and tests two complementary morphometric procedures for pairwise comparison of ceramic vessels. The first uses analytically defined vessel parts and compares their proportional and angular properties; the second measures similarity in the continuous curvature of vessel profiles. Both approaches are designed to distinguish similarity patterns that reflect shared production practice from those that fall within ordinary variation in traditional pottery.

Validation on large experimental and ethnographic datasets shows that vessel form preserves a reproducible signal of production-unit-specific practice, but that the strength of this signal depends on the degree of technological standardization. The two procedures are not interchangeable: each captures different aspects of morphological variability, and their limited overlap indicates complementarity rather than redundancy. Application of the methods to the Roman-period cemetery of Frontovoe 3 in southwestern Crimea shows that morphologically linked vessels tend to occur in graves that are close in date, suggesting that ceramic similarity may also serve as an auxiliary chronological indicator. The study therefore offers a more explicit and reproducible basis for typological reasoning in archaeology.

1. Introduction

1.1. Research problem

Contemporary archaeology increasingly addresses questions that require methods beyond traditional archaeological analysis. These include mobility, diet, lifeways, genetic profiles, and many other topics (Abdelhady et al. 2024; Bethard and Tung 2021; Jiménez-Manchón et al. 2023). Within archaeology's so-called third science revolution (Kristiansen 2021), it might seem that theoretical and methodological debates concerning typology and classification have lost their relevance and that the period of active discussion is over (Spaulding 1953; Dunnell 1971; Read 1974). Yet any major discovery emerging from an interdisciplinary paradigm is eventually integrated into the cultural-chronological frameworks built by archaeologists with the discipline's traditional tools: typology and classification (Adams 1988; Bortolini 2016). Throughout most of archaeology's history, these methods have remained foundational because they address one of the core tasks of the discipline: organizing material in time and space. For this reason, discussions of their limitations and attempts to overcome them remain highly relevant. Efforts to improve these methods strengthen the evidential basis of cultural-historical interpretation, regardless of the broader research paradigm in which such interpretations are developed.

A central issue in this debate concerns the boundary between the analytical constructs created by archaeologists and the social realities these constructs are meant to reflect (Spaulding 1953; Ford and Steward 1954; Binford 1965; Whittaker et al. 1998; Riede et al. 2022). Put simply, how finely should archaeological finds be divided into classes, types, and variants so that the resulting taxonomy mirror

ancient phenomena and processes rather than the researcher's subjective judgment? Unfortunately, archaeologists have limited means of assessing what proportion of artifact variability is caused by social, technological, or chronological factors and what proportion reflects chance and the inevitable noise associated with handmade production. Classifying archaeological material without understanding this variability risks creating formal taxonomy that distort the relationship between material culture and the behavior of the people who produced it. At the same time, archaeological contexts are often too sparse to separate the social, chronological, and other factors contributing to variability in ancient material culture.

One promising response to this problem has been developed in pottery studies, drawing extensively on experimental and ethnographic data. This approach seeks criteria that would allow archaeologists to distinguish, in ancient material, objects belonging to the same production unit (Kramer 1985: 84, 87; Longacre 1991: 110). Such a unit may be loosely termed «one potter» or «same potter», while recognizing that it may refer either to an individual or to a group of potters sharing the same *chaîne opératoire* and common learning networks (Graves 1991; Roux and Courty 1998; Gosselain and Stark 1998; Gosselain 2000). This is a difficult task, but it may bring us closer to an appropriate level of subdivision in ceramic classification, because «one potter» is among the finest levels of taxonomic division in ceramics that can still carry social meaning.

1.2. Current state of the problem

Recent research shows that fingerprints on the surfaces of clay artefacts can provide reliable evidence of authorship (Branigan et al. 2002; Fowler et al. 2019; Ross et al. 2023). However, despite their potential, fingerprint analysis remains rare and is not yet a routine, widely accessible tool. For archaeologists, vessel form is a much more readily available and widespread source of evidence. Thanks to the work of E. Gandon, V. Roux, A. Karasik, O. Harush, and others, substantial progress has recently been made in developing methods for distinguishing maker-specific signatures in ceramic morphology (Gandon et al. 2018; 2021; Roux and Karasik 2018; Harush et al. 2019; 2020). At present, these are the most directly relevant studies on the topic under consideration. Experimental studies based on traditional pottery in Palestine, India, and Nepal have convincingly shown that even in assemblages of vessels that appear intuitively «identical», statistical procedures can detect a signal reflecting the individual or group identity of their makers. Vessels produced by the same potter generally show greater similarity than vessels made by different potters. Individual differences are most often expressed in subtle variations in the upper parts of vessels, which the authors of these studies regard as a particularly informative source of morphological signal. Similar results were obtained in experiments with ceramic students at the Bezalel Academy of Arts and Design (Jerusalem). Replicas of a jug neck showed that an individual signature can appear even among beginners (Harush et al. 2019).

Collectively, these studies show that ceramic vessel forms do indeed carry markers of individual or group identity. For that reason, the search for ways to identify those markers in ancient material is entirely justified. However, one crucial methodological problem remains unresolved: no stable and easily

transferable procedures have yet been proposed for archaeological analysis that would allow patterns documented in traditional pottery with known authorship to be used in its study.

The present article contributes to that line of research. It proposes an original method for identifying series of vessels made by the same production unit on the basis of ceramic form. One important caveat should be stated at the outset. We do not assume that universal morphological markers of authorship can be found and made to work consistently across diverse archaeological ceramics. Instead, we focus on a different task: determining quantitative measures of similarity between ceramic forms that characterize traditional products of the same potter and are not typical of vessels made by different people. In our view, this is the practical threshold beyond which further subdivision of ceramics no longer has analytical value.

2. Research design and materials

The proposed technique is based on a relatively simple procedure suitable for ethnographic and experimental material, as well as archaeological assemblages. It involves pairwise comparison of vessel forms and calculation of the degree of similarity within each pair. The resulting similarity measure is constant for any given pair and does not depend on the size or diversity of the sample, which is not always the case with multivariate methods such as cluster analysis or principal components analysis (Shennan 1997). The central aim of this study is to determine the level of pairwise similarity at which one may reasonably infer, in archaeological analysis, that two vessels were made by the «same potter» or same production unit.

To address this problem, we need a large series of vessels made by different potters according to their own individual standards. In this study, that material comes from ceramic collections assembled by the Complex Expedition for the Study of Pottery under the direction of the renowned Russian archaeologist and specialist in ancient pottery A. A. Bobrinsky (1978). The expedition worked in the 1970s and 1980s across the territory of the former USSR, mainly in the forest and forest-steppe zones of Eastern Europe, where several hundred rural and urban pottery-production sites oriented toward market distribution were documented (Tsetlin 2017). All vessels considered in this article were made by professional potters with decades of experience. The vessels were produced on two types of pottery wheel: kick wheels and hand-operated wheels.

The vessels analyzed here resulted from a simple experimental task given to these potters: to produce a series of several vessels of a traditional form that they regularly reproduce. A complete list of the potters and vessels used in the study is provided in the Tables 1 and 2. The total sample comprises 556 vessels made by 28 different potters. In some cases, vessels attributed to a given potter include products made in different years of the expedition’s fieldwork.

All of these vessels are functionally homogeneous: pots with broadly similar proportions and outlines. For analysis, the sample was divided into two parts: a main sample and a test sample. The main sample was used to calculate threshold levels of pairwise similarity in ceramic form characteristic of products

by the same maker. The test sample was used to validate these thresholds and assess their robustness. The main sample consisted of 264 vessels made by 16 potters (Table 1; Fig. 1), whereas the test sample comprised 292 vessels made by 12 potters (Table 2; Fig. 2). In assembling the test sample, we deliberately included potters whose forms are visually the most difficult to distinguish. This was a deliberate choice, because it allowed us to test whether the identified thresholds would hold under «difficult conditions».

Sixteen potters were included in the main sample, all of them working on kick wheels. The test sample included both kick wheel potters (eight individuals) and hand-operated wheel potters (four individuals). This design was justified by the need to identify the optimal conditions for applying the method depending on the degree of technological refinement of the pottery under study. Our initial hypothesis was that vessels made on kick wheels would be more standardized and therefore require stricter thresholds than vessels made on hand-operated wheels. This matters because pottery from archaeological sites varies widely in manufacturing sophistication.

Table 1
Potters included in the main sample

Potter's surname		Residence	Wheel type	Number of vessels identified by the second method	Number of vessels identified by the first method	Years of production
1	Denisenko	Information is lost	Kick wheel	10	9	1980
2	Evdokimov	Rogachev, Belarus	Kick wheel	29	28	1974–1976
3	Gadzik	Olkhovka, Transcarpatian region, Ukraine	Kick wheel	10	10	1974
4	Galas M.	Olkhovka, Transcarpatian region, Ukraine	Kick wheel	10	10	1980
5	Galas Yu.	Olkhovka, Transcarpatian region, Ukraine	Kick wheel	8	8	1974
6	Garalsky	Troyanov, Zhitomir region, Ukraine	Kick wheel	20	17	1978–1979
7	Gorely	Radomyshl, Zhitomir region, Ukraine	Kick wheel	10	10	1974
8	Kocheniuk	Tsarevka, Zhitomir region, Ukraine	Kick wheel	39	37	1974–1976, 1978, 1980
9	Kot	Oleshnya, Chernigov region, Ukraine	Kick wheel	17	17	1979–1980
10	Kulek	Information is lost	Kick wheel	9	9	1979
11	Kulikovsky	Information is lost	Kick wheel	17	17	1978–1979
12	Malik	Filimonovo, Tula region, Russia	Kick wheel	10	10	1975
13	Mamavka	Information is lost	Kick wheel	7	7	1980
14	Medvedsky	Shumyachi, Smolensk region, Russia	Kick wheel	30	28	1974–1976

Potter's surname		Residence	Wheel type	Number of vessels identified by the second method	Number of vessels identified by the first method	Years of production
15	Velichko	Information is lost	Kick wheel	10	8	1979
16	Vender	Troyanov, Zhitomir region, Ukraine	Kick wheel	28	25	1978–1980
Total				264	250	

Table 2
Potters included in the test sample

Potter's surname		Residence	Wheel type	Number of vessels identified by the second method	Number of vessels identified by the first method	Years of production
1	Medvediuk	Troyanov, Zhitomir region, Ukraine	Kick wheel	38	26	1974, 1978–1980
2	Panchenko	Ivankovtsy, Zhitomir region, Ukraine	Kick wheel	30	30	1978–1980
3	Rymorenko	Radomyshl, Zhitomir region, Ukraine	Kick wheel	50	45	1974–1976, 1978
4	Skladovskaya	Troyanov, Zhitomir region, Ukraine	Kick wheel	10	10	1974
5	Slavinsky	Troyanov, Zhitomir region, Ukraine	Kick wheel	19	12	1978–1979
6	Sych	Information is lost	Kick wheel	10	10	1978
7	Turovets	Information is lost	Kick wheel	27	27	1978–1980
8	Shcherbach	Radomyshl, Zhitomir region, Ukraine	Kick wheel	30	30	1978–1980
9	Kanishchev	Tula, Russia	Hand-operated wheel	30	29	1976, 1978, 1980
10	Malygin	Tula, Russia	Hand-operated wheel	10	10	1974
11	Vlasov A.	Tula, Russia	Hand-operated wheel	19	19	1974–1975
12	Vlasov K.	Tula, Russia	Hand-operated	19	19	1974–1975

Potter's surname	Residence	Wheel type	Number of vessels identified by the second method	Number of vessels identified by the first method	Years of production
		wheel			
Total			292	267	

3. Method

The study is based on 2D contour images of vessels. We could not use more advanced analytical techniques such as 3D models because the material was collected in the second half of the twentieth century. The ceramic vessels were photographed in the field by members of the Complex Expedition in strict frontal view. These photographs were converted into 2D contour images and then scaled to a common height while preserving proportions. Because we cannot be certain that the photographic angle in every case captured the vessel's «typical» profile, a mean contour was generated for each vessel, smoothing asymmetry between the left and right halves. This procedure was performed automatically using a specially prepared Python script.

We now turn to the method itself. The article considers two analytical approaches that differ in the information about form variation used in pairwise comparisons of clay vessels.

The first approach may be termed the key-point method. It builds on A. A. Bobrinsky's procedure for ceramic-form analysis, widely used in Russian-language archaeology (Bobrinsky 2018a; 2018b; 2018c; Sukhanov 2020a; 2020b; 2021). Points marking «extreme» changes in the contour (Fig. 3: 2, A) are identified on the vessel outline by means of circular templates (Fig. 3: 2, B). These are the segments where the contour changes markedly – for example, where concave sections of the outline turn into convex ones. The result is a division of the vessel into several parts, whose boundaries are defined by the points identified on the contour (Fig. 3: 3). The number of such parts may vary. Nearly 90% of the vessels in the main sample are represented by forms with three analytical parts: body (Fig. 3: C, F), shoulder (Fig. 3: D, G), and neck (Fig. 3: E, H). The remaining vessels have a more complex structure, cannot be compared with the main group, and were therefore excluded from further analysis within the first approach.

For each vessel part, two parameters were measured: angle of inclination (Fig. 3: C, D, E) and proportionality (Fig. 3: F, G, H) (height divided by the arithmetic mean of the two bases). Both are relative measures, which makes them especially useful for form analysis because they abstract away from absolute size. These steps yield six morphological parameters for each vessel.

The central analytical step is the pairwise comparison of vessels made by the same potter and by different potters. Comparison was based on a simple similarity coefficient defined as the smaller value divided by the larger one. The similarity coefficient therefore ranges from 0 to 1. The closer the value is

to 1, the greater the similarity. This makes the metric easy to interpret and suitable for comparing morphological variables expressed in different units, such as inclination angle and proportionality in our case. For example, for two vessels with body inclination angles of 70.1° and 70.3°, the similarity coefficient is 0.997, whereas for vessels with values of 70.0° and 80.0°, it is 0.875.

Pairwise comparisons were performed automatically using a specially prepared Python script. Comparison of all vessels in the main sample yielded six similarity coefficients across 31125 unique pairs, including 2459 pairs of vessels made by the same potter and 28666 pairs made by different potters. The subsequent processing of these data is described in the next section.

Where the first approach captures point-based patterns in the distribution of potters' physical effort in constructing vessel form, the second focuses directly on the curvilinear outline of the vessel profile and abstracts from the inclination angles and proportions of its constituent parts. It also allows vessels with any number of parts to be compared, regardless of the number of «key points» on the contour, and therefore, unlike the first approach, it enabled us to use the entire main sample.

This approach uses the same set of 2D images of ceramic forms containing the vessel's mean contour (Fig. 4: 1). Using a specially prepared Python script, two points were manually marked on each contour – one at the upper edge and one at the lower edge (Fig. 4: 2, A). The curve between these points represents the vessel's full vertical profile (Fig. 4: 2, B). To ensure comparability between vessels of different sizes, all segments defined in this way were normalized to a common notional height of 500 mm.[1] The points at the upper and lower edges of the profile were automatically connected by a straight line, referred to here as the base chord (Fig. 4: 2, C). In this case, the quantitative description of vessel form reduces to radial measurements of the distance from the chord to the contour at regular intervals. Empirical testing showed that the most informative results were obtained with a detailed measurement scheme using a 10 mm step (Fig. 4: 3). Under this scheme, the form of each vessel is represented by 51 measurements from the chord to the profile; 49 points are under analysis.[2]

As in the first approach, the measurements for vessels in the main sample – both within individual series and across vessels made by different potters – were compared pairwise using a Python script that calculated similarity coefficients for each measurement point. Here, the similarity coefficient indicates the extent to which the curvatures of two vessels coincide at a specific point along the profile. The number of unique pairs compared was 34716, including 2777 pairs from individual series and 31939 pairs made by different potters.

A technical note is necessary here. During measurement, we found that in some cases the vessel contour (Fig. 4: B) intersects the chord connecting the upper and lower edges of the profile (Fig. 4: C). In such cases, the distances between contour and chord become negative, which is inconvenient for subsequent pairwise comparison using a similarity coefficient. Alternative metrics that could handle both negative and positive values would unnecessarily complicate an already technically demanding study. To avoid this, the straight line connecting the upper and lower boundaries of the contour was

shifted parallel by 60 mm (Fig. 4: 3, D). This shift was sufficient to ensure that the chord no longer intersected the contour and that all measured values were positive. All vessels considered in this article were prepared and measured according to these rules.

4. Results

4.1. Key-point analysis

4.1.1. Determining similarity thresholds (main sample)

Here we analyze the results of pairwise similarity calculations for vessels across six morphological parameters: neck inclination, neck proportionality, shoulder inclination, shoulder proportionality, body inclination, and body proportionality. Our first task is to determine how effectively these variables distinguish the products of different potters. To that end, we calculated the mean similarity coefficient for each variable within two categories in the main sample: pairs of vessels made by the same potter and pairs made by different potters (Table 3). We acknowledge the limitations of averaging, but given the very large size of the material analyzed – several thousand pairs in each category – this is entirely acceptable.

Table 3
Mean within-class and between-class similarity by form parameter in the key-point method

Form parameters		Within-class mean	Between-class mean	Within-class std. dev.	Between-class std. dev.	Difference between within- and between-class means	Group
1	Neck inclination	0.939	0.868	0.049	0.093	0.072	A
2	Neck proportionality	0.847	0.766	0.107	0.149	0.081	A
3	Shoulder inclination	0.970	0.945	0.024	0.039	0.024	B
4	Shoulder proportionality	0.879	0.795	0.091	0.130	0.084	A
5	Body inclination	0.968	0.946	0.025	0.038	0.022	B
6	Body proportionality	0.894	0.842	0.081	0.107	0.052	A

As an indicator of discriminative power, we used the difference between the mean within-class and between-class similarity values (Table 3). Four variables show relatively higher discriminative power. The calculated values fall in the 0.05–0.08 range. These are neck inclination (Fig. 5: 1), neck proportionality

(Fig. 5: 2), shoulder proportionality (Fig. 5: 4), and body proportionality (Fig. 5: 6). We designate these as «Group A» variables. The other two parameters – shoulder inclination (Fig. 5: 3) and body inclination (Fig. 5: 5) – designated «Group B» variables, have markedly lower values, around 0.02.

We therefore concluded that, in pairwise comparison, Group A variables discriminate ceramic forms produced by different potters substantially better than Group B variables. Two implications follow. First, within each group the variables are broadly equivalent in the amount of information they provide about the «individual signature». Second, Group A captures differences between vessels made by different potters more effectively than Group B. This, however, does not justify excluding Group B from further analysis. A more appropriate solution is to reduce the number of variables in subsequent calculations from six to two by taking the mean similarity of vessels across Group A variables (SA) and the mean similarity across Group B variables (SB). This simplifies the analytical procedure and reduces the influence of random fluctuations.

We must now answer the key question of this study: at what levels of pairwise similarity between ceramic forms can we reasonably suggest, in archaeological analysis, that two vessels may have been made by the same production unit? To do so, we need to analyze the distribution of within-class and between-class SA and SB values in the main sample and identify threshold similarity values that minimize the number of between-class pairs while maximizing the number of within-class pairs.

Threshold selection rests on the assumption that between-class pairs (different potters) constitute the noise background that must be filtered out. If a threshold T is chosen so that only a small proportion of between-class pairs exceeds it, then any pair with similarity above T is highly likely to be within-class. Naturally, such thresholds correspond to the high percentiles of the between-class similarity distribution. We tested percentiles from 80 to 99.9 (80, 85, 90, 95, 99, and 99.9), which made it possible to vary the strictness of the criterion: a higher percentile reduces the probability that a between-class pair will be mistakenly attributed to the same potter (fewer false positives), but it also reduces the proportion of within-class pairs that satisfy the condition (lower sensitivity).

For each threshold, we calculated the proportion of within-class pairs whose similarity exceeded the threshold. This share, known as the true positive rate (TPR), characterizes the sensitivity of the criterion: it shows what proportion of products by the same potter can be correctly identified at a given level of strictness. The higher the TPR, the more same-potter pairs we capture, but the greater the risk of including between-class pairs (false positives). Thus, the choice of percentile depends on the balance between completeness (TPR) and precision that is acceptable for a given research task.

Table 4 presents the threshold values calculated directly from the full main sample and the corresponding TPRs. For the Group A variables, thresholds range from 0.8798 (80th percentile) to 0.9719 (99.9th percentile), while TPR declines from 62.4% to 2.0%. For the Group B variables, thresholds for the selected percentiles fall in the 0.9701–0.9981 range (as expected, because these variables were previously shown to distinguish the potters in the main sample less effectively), and TPR decreases from 56.9% to 0.4%.

These data clearly show that the stricter the thresholds we apply to archaeological identification of the same production unit, the fewer pairs will be detected as genuinely belonging to that unit (TPR), but the higher the accuracy will be.

Before moving on to validation on the test sample, however, we must assess how robust these thresholds are. The main sample used to derive them, although large, is still random in character. We cannot be fully certain that the values obtained were not influenced by some specific features of this particular set of vessels.

To evaluate threshold robustness, we applied repeated subsampling without replacement (Politis et al. 1999). From the main sample, 250 vessels were randomly drawn 1000 times, and for each subsample, the same percentiles of the between-class SA and SB distributions were recalculated. The results are shown in Table 5. The mean threshold values across the subsamples are virtually identical to those obtained from the full sample (Table 4). Standard deviations are extremely small: for Group A, they range from 0.0010 to 0.0018, and for Group B, from 0.0002 to 0.0006. The 95% confidence intervals are very narrow; for example, for the 80th percentile of Group A, the interval is 0.8766–0.8835. This indicates that the thresholds are highly stable: even with substantial variation in subsample composition, the percentiles of the between-class distributions are reproduced with high precision.

Table 5
Robustness of key-point thresholds across repeated subsamples

percentile	form parameters	Mean	Median	Std. dev.	95% CI
80.0	A-group (SA)	0.8800	0.8799	0.0018	0.8766–0.8835
	B-group (SB)	0.9701	0.9701	0.0006	0.9690–0.9713
85.0	A-group	0.8906	0.8905	0.0016	0.8876–0.8939
	B-group	0.9744	0.9745	0.0006	0.9734–0.9756
90.0	A-group	0.9037	0.9038	0.0016	0.9055–0.9068
	B-group	0.9797	0.9797	0.0005	0.9788–0.9806
95.0	A-group	0.9214	0.9214	0.0014	0.9186–0.9241
	B-group	0.9859	0.9858	0.0004	0.9852–0.9865
99.0	A-group	0.9496	0.9497	0.0013	0.9470–0.9518
	B-group	0.9938	0.9938	0.0002	0.9934–0.9943
99.9	A-group	0.9717	0.9719	0.0010	0.9689–0.9731
	B-group	0.9981	0.9981	0.0002	0.9977–0.9983

Table 4
Threshold values and true positive rates for the key-point method

percentile	form parameters	thresholds	TPR (%)
80.0	A-group (SA)	0.8798	62.4
	B-group (SB)	0.9701	56.9
85.0	A-group	0.8904	53.2
	B-group	0.9745	47.7
90.0	A-group	0.9037	42.6
	B-group	0.9797	35.6
95.0	A-group	0.9214	28.5
	B-group	0.9859	20.3
99.0	A-group	0.9497	9.4
	B-group	0.9938	4.8
99.9	A-group	0.9719	2
	B-group	0.9981	0.4

We therefore have sufficient grounds to treat the pairwise similarity thresholds established at different strictness levels (85th-99.9th percentiles) as reliable, robust, and suitable for application to new ceramic collections.

4.1.2. Threshold validation (test sample)

4.1.2.1. Kick wheel pottery

Validation of the pairwise similarity thresholds corresponding to different between-class percentiles from the main sample was conducted on 189 vessels made by eight different potters on kick wheels. Validation was performed for each of the six strictness levels corresponding to the 80th, 85th, 90th, 95th, 99th, and 99.9th percentiles of the between-class distributions. For each level, the threshold values TA and TB obtained earlier from the main sample were used (see Table 4).

In the test sample, mean similarity values for the Group A variables (SA) and Group B variables (SB) were calculated for every pair of vessels. A pair was considered to have passed the threshold if both SA ≥ TA and SB ≥ TB. We then determined what proportion of such pairs were actually formed by vessels made by the same potter.

Because the composition of the test sample is fixed, whereas the size of real archaeological collections may vary, we additionally assessed result stability at different sample sizes. To do so, repeated

subsampling without replacement was used. For each sample size n = 30, 80, 130, and 180, 1.000 random subsamples were drawn from the test collection. For each subsample, the share of «true» pairs among those passing the threshold was calculated. The resulting distributions made it possible to compute mean values, medians, standard deviations, and confidence intervals for the proportion of correct identifications at each strictness level and each sample size (Table 6).

Table 6
Validation of key-point thresholds on kick wheel pottery

Percentile	Sample size	Median identification accuracy (%)	Std. dev. (proportion), %	95% CI (accuracy)	Median number of pairs	Std. dev. (pairs)	95% CI (pairs)
80	30	31.4	6.9	21.4–47.4	109	20.9	76–156
	80	31.7	2.9	27.1–38.2	805	71.1	684–959
	130	31.7	1.6	28.8–35.0	2158	106.3	1959–2375
	180	31.7	0.5	30.7–32.8	4146	68.2	4006–4281
85	30	35.7	7.9	23.0–53.1	77	15.9	50–115
	80	35.7	3.3	30.1–42.9	569	55.7	471–691
	130	35.7	1.8	32.3–39.4	1514	85.1	1350–1685
	180	35.8	0.6	34.8–37.0	2906	53.2	2802–3008
90	30	42.5	9.8	25.0–62.8	43	10.8	27–69
	80	42.1	4.1	34.8–50.6	325	37.0	262–409
	130	42.1	2.2	38.0–46.6	867	55.2	768–973
	180	42.2	0.8	40.9–43.9	1666	34.5	1593–1726
95	30	53.3	14.0	27.8–81.8	16	5.5	8–30
	80	52.5	5.4	42.7–64.2	123	16.7	97–161
	130	52.8	2.9	47.2–58.7	327	24.7	282–379
	180	52.7	0.9	51.0–54.6	632	15.3	600–657
99	30	66.7	45.6	0.0–100.0	1	1.2	0–4
	80	80.0	14.5	44.4–100.0	9	3.2	4–17

Percentile	Sample size	Median identification accuracy (%)	Std. dev. (proportion), %	95% CI (accuracy)	Median number of pairs	Std. dev. (pairs)	95% CI (pairs)
	130	77.8	6.7	63.6–89.7	25	4.4	17–34
	180	77.6	2.0	73.9–81.8	49	2.8	43–53
99.9	30	0.0	18.1	0.0–100.0	0	0.2	0–1
	80	0.0	46.3	0.0–100.0	0	0.5	0–1
	130	100.0	44.6	0.0–100.0	1	0.7	0–2
	180	100.0	7.7	100.0–100.0	2	0.4	1–2

The data reveal the expected relationship between threshold strictness and performance. At low thresholds (80th–85th percentiles), the number of pairs passing the filter is maximal (from about 2900 to 4100), but identification accuracy remains low – around 32–36%. This means that roughly two-thirds of the pairs satisfying the criterion actually belong to different potters, making such thresholds unsuitable for our purpose.

Raising the threshold to the 90th and 95th percentiles improves accuracy to about 42–53%, but at the same time the number of identified pairs falls sharply compared with the 80th percentile. This is an expected outcome: stricter criteria reduce false positives, but they also reduce coverage of same-potter pairs.

The best balance is obtained at the 99th percentile. At a sample size of 180 vessels, mean accuracy reaches 77.6% (95% CI: 73.9–81.8%), and the mean number of pairs passing the threshold is 49 (95% CI: 43–53). Such a sharp reduction in the number of pairs relative to less strict thresholds is expected, because the criterion filters out the overwhelming majority of between-class comparisons, leaving only the most similar pairs.

The 99.9th percentile threshold yields absolute accuracy (100%); however, the cost is an extremely small number of identified pairs: at a sample size of 180 vessels, the mean is only 2 pairs, and in smaller collections (30–80 vessels) it often drops to zero or one. This makes this level of strictness impractical for archaeological analysis.

Accordingly, the optimal balance between accuracy and the number of diagnostically useful pairs for pottery made on kick wheels is provided by the threshold corresponding to the 99th percentile of the between-class distributions in the main sample. In the test sample, this threshold yields an average of about 78% true same-potter pairs, which is an acceptable result for archaeological analysis. Examples of some vessel pairs correctly identified as products of the same potter are shown in Fig. 8; examples of «misclassified» pairs are shown in Fig. 9. Further tightening of the criterion (99.9th percentile) is not

advisable, because it sharply reduces the number of analyzable pairs without any substantial gain in accuracy.

4.1.2.2. Hand-operated wheel pottery

Analysis of the ceramic series made by four different potters enabled us to determine the optimal strictness thresholds for hand-operated wheel pottery. The analysis followed the same procedure as for kick wheel pottery. The only difference was that, because the test sample was much smaller (77), robustness testing used smaller subsamples: 30, 50, and 70 vessels.

The results (Table 7) show a pattern different from that observed for the kick wheel pottery. Here, a high level of accuracy is already achieved at the 80th percentile threshold – on average 79.5% (95% CI: 76.3–85.7%) – and the number of identified pairs is maximal, at 116 for a sample of 70 vessels. This relatively high accuracy at a lenient threshold is probably explained by greater within-group variability in hand-operated wheel forms: even vessels made by the same potter differ noticeably, so the SA and SB values for “true” pairs do not reach the same high levels as on kick wheel pottery. At the same time, inter-class differences are even more pronounced, which produces good separation already at the 80th percentile.

Table 7
Validation of key-point thresholds on hand-operated wheel pottery

Percentile	Sample size	Median identification accuracy (%)	Std. dev. (proportion), %	95% CI (accuracy)	Median number of pairs	Std. dev. (pairs)	95% CI (pairs)
80	30	81.0	10.7	59.1–100.0	21	5.4	12–33
	50	80.3	6.3	68.4–91.8	59	7.8	45–75
	70	79.5	2.5	76.3–85.7	116	6.0	103–127
85	30	76.9	13.7	50.0–100.0	12	3.7	6–20
	50	77.1	7.1	63.6–91.2	34	5.4	25–46
	70	76.7	2.9	72.7–83.9	69	4.2	60–76
90	30	84.6	15.9	50.0–100.0	7	2.9	2–14
	50	83.3	7.9	68.4–100.0	20	4.0	13–28
	70	82.5	3.0	77.8–89.7	39	3.2	32–45
95	30	100.0	36.0	0.0–100.0	2	1.3	0–5
	50	80.0	14.7	50.0–100.0	6	1.8	3–9
	70	77.8	5.3	70.0–90.9	12	1.4	9–14
99	30	0.0	0.0	0.0–0.0	0	0.0	0–0
	50	0.0	0.0	0.0–0.0	0	0.0	0–0
	70	0.0	0.0	0.0–0.0	0	0.0	0–0
99.9	30	0.0	0.0	0.0–0.0	0	0.0	0–0
	50	0.0	0.0	0.0–0.0	0	0.0	0–0
	70	0.0	0.0	0.0–0.0	0	0.0	0–0

Increasing the threshold to the 85th percentile barely changes accuracy (76.7%) but almost halves the number of identified pairs (to 69) (Table 7). Moving to the 90th percentile yields the highest accuracy (82.5%), but the number of pairs decreases to 39. The 95th percentile does not improve accuracy further (77.8%) and reduces the number of pairs to 12. At such a low number of pairs, meaningful analysis of an archaeological collection becomes problematic, especially because real samples are often smaller than 70 vessels.

For the most stringent thresholds (99th and 99.9th percentiles), no pair satisfying the criteria was found in the test sample. This is unsurprising, since on a hand-operated wheel even same-potter pairs rarely achieve such high similarity, and thresholds derived from highly standardized kick wheel pottery prove excessively strict, completely blocking diagnosis.

Thus, for hand-operated wheel pottery, the optimal strictness level is the 80th percentile of the between-class distributions in the main sample. At this threshold, approximately 80% of the identified pairs in the test sample are indeed made by the same potter, and the number of pairs (around 115 for a sample of 70 vessels) is sufficient for drawing defensible conclusions. Further tightening of the criterion is not advisable, because it sharply reduces the number of diagnostically useful pairs without any substantial gain in accuracy.

4.2. Analysis of curvilinear vessel profiles

4.2.1. Determining similarity thresholds (main sample)

As in the first approach (key-point method), the first step was to assess the discriminative power of the measurements collected. For each of the 49 points, mean similarity coefficients were calculated for pairs of vessels made by the same potter and for pairs made by different potters. As before, the difference between mean within-class and between-class similarity was used as the measure of a point's discriminative power (Table 8).

Table 8
Mean within-class and between-class similarity by profile point in the curvature method

Point number	Within-class mean	Between-class mean	Within-class std. dev.	Between-class std. dev.	Difference between within- and between-class means	Group
2	0.945	0.942	0.051	0.050	0.004	-
3	0.938	0.924	0.056	0.059	0.014	-
4	0.932	0.904	0.059	0.072	0.027	B
5	0.926	0.878	0.063	0.088	0.048	B
6	0.919	0.833	0.066	0.112	0.086	A
7	0.908	0.785	0.071	0.139	0.123	A
8	0.902	0.763	0.074	0.155	0.139	A
9	0.905	0.766	0.075	0.157	0.140	A
10	0.911	0.777	0.074	0.154	0.134	A
11	0.918	0.792	0.070	0.147	0.126	A
12	0.925	0.808	0.066	0.139	0.117	A
13	0.931	0.823	0.061	0.131	0.108	A
14	0.936	0.836	0.057	0.123	0.099	A
15	0.940	0.849	0.053	0.114	0.091	A
16	0.944	0.860	0.049	0.106	0.084	A
17	0.947	0.871	0.046	0.097	0.076	A
18	0.949	0.881	0.044	0.089	0.069	B
19	0.951	0.890	0.041	0.082	0.061	B
20	0.953	0.899	0.040	0.075	0.054	B
21	0.954	0.906	0.038	0.069	0.047	B
22	0.954	0.913	0.037	0.063	0.041	B
23	0.955	0.920	0.037	0.059	0.035	B
24	0.955	0.925	0.036	0.055	0.030	B
25	0.955	0.930	0.036	0.051	0.026	B
26	0.955	0.933	0.036	0.049	0.022	B

Point number	Within-class mean	Between-class mean	Within-class std. dev.	Between-class std. dev.	Difference between within- and between-class means	Group
27	0.956	0.935	0.036	0.048	0.020	B
28	0.956	0.936	0.036	0.048	0.019	B
29	0.955	0.936	0.037	0.048	0.019	B
30	0.955	0.935	0.037	0.049	0.020	B
31	0.954	0.932	0.038	0.051	0.022	B
32	0.954	0.929	0.038	0.053	0.025	B
33	0.953	0.925	0.039	0.055	0.028	B
34	0.952	0.921	0.040	0.057	0.031	B
35	0.951	0.916	0.040	0.060	0.035	B
36	0.950	0.911	0.041	0.062	0.038	B
37	0.948	0.906	0.042	0.065	0.042	B
38	0.947	0.901	0.043	0.068	0.046	B
39	0.945	0.895	0.044	0.071	0.050	B
40	0.943	0.890	0.045	0.073	0.053	B
41	0.942	0.885	0.045	0.076	0.057	B
42	0.941	0.879	0.045	0.079	0.062	B
43	0.941	0.874	0.045	0.082	0.066	B
44	0.940	0.870	0.045	0.084	0.070	B
45	0.939	0.868	0.045	0.087	0.072	B
46	0.939	0.870	0.046	0.086	0.069	B
47	0.939	0.878	0.048	0.082	0.061	B
48	0.935	0.890	0.056	0.080	0.045	B
49	0.936	0.904	0.055	0.074	0.032	B
50	0.956	0.941	0.034	0.045	0.015	-

On this basis, we attempted to allocate the most informative segments of the profile. The plot of the distribution of mean differences (intra minus inter) across points (Fig. 6) shows the following pattern:

beginning at point 6, the indicator rises sharply, forming a pronounced plateau across points 6–17 and then gradually declining. A second zone of increase lies in the range of points 34–48.

We can see that, as in the first analytical approach, the selected morphological features are not equally effective in distinguishing potters. For the sake of analytical convenience, we can therefore use the same strategy: aggregate the numerous variables into two compact groups distinguished by their discriminative power.

The rationale for the point-group boundaries proposed below is shown in Fig. 7. We decided that Group A would include the most informative points 6–17 (12 points in total), for which intra-inter > 0.09 (Fig. 6: A). Group B (the less informative points) includes points 4, 5, and 18–49 (34 points in total), with intra-inter values in the 0.03–0.08 range (Fig. 6: B). Points 2, 3, and 50, which have very low discriminative power, were excluded from further analysis as clearly uninformative.

The next stage, analogous to the procedure described in Section 4.1.1, involved moving from point-by-point descriptions to integral similarity measures for the two groups. For each unique pair of vessels in the main sample, two values were calculated: SA – the arithmetic mean of similarity coefficients across the 12 points of Group A - and SB – the arithmetic mean across the 34 points of Group B. As before, these integral measures lie in the interval [0.1], where 1 denotes complete coincidence of the profiles at all points in the respective group. Using group means not only simplifies the analysis but also reduces the influence of random outliers at individual points.

Next, for the set of between-class pairs (different potters), distributions of SA and SB were constructed, and their high percentiles – 80, 85, 90, 95, 99, and 99.9 – were determined. These values are taken as threshold values TA and TB for the corresponding strictness levels. The logic of threshold selection is fully analogous to that described in Section 4.1.1: the threshold filters out a specified share of the most similar between-class pairs that might otherwise be mistakenly treated as «the same potter». The resulting threshold values are given in Table 9. For each threshold, we also calculated the share of within-class pairs whose similarity exceeded it (the true positive rate, TPR), which characterizes the sensitivity of the criterion.

Table 9
Threshold values and true positive rates for the curvature method

Percentile	form parameters	thresholds	TPR (%)
80.0	A-group (SA)	0.9253	59.2
	B-group (SB)	0.9423	66.2
85.0	A-group	0.9376	50.6
	B-group	0.9488	59.0
90.0	A-group	0.9491	41.1
	B-group	0.9565	48.4
95.0	A-group	0.9623	27.7
	B-group	0.9658	33.0
99.0	A-group	0.9780	10.2
	B-group	0.9787	10.0
99.9	A-group	0.9879	1.8
	B-group	0.9874	1.4

As Table 9 shows, increasing threshold strictness leads, as expected, to a decrease in the share of «true» pairs satisfying the criterion. For Group A, TPR falls from 59.2% at the 80th percentile to 1.8% at the 99.9th percentile; for Group B, it falls from 66.2% to 1.4%. The thresholds for Group A are lower than those for Group B, reflecting the different similarity distributions of the two groups. The choice of a specific percentile for further application will depend on the balance between the desired precision (minimizing false positives) and the desired coverage of within-class pairs.

Before turning to validation on the test collections, the robustness of the resulting values must be established. For this purpose, as in the previous section, repeated subsampling without replacement was used. From the main sample, 250 vessels were randomly drawn 1000 times, and the percentiles of the between-class SA and SB distributions were recalculated for each subsample. The results are presented in Table 10.

Table 10
Robustness of curvature thresholds across repeated subsamples

percentile	form parameters	Mean	Median	Std. dev.	95% CI
80.0	A-group (SA)	0.9253	0.9252	0.0020	0.9213–0.9295
	B-group (SB)	0.9423	0.9423	0.0011	0.9401–0.9444
85.0	A-group	0.9375	0.9375	0.0016	0.9346–0.9406
	B-group	0.9488	0.9489	0.0011	0.9468–0.9509
90.0	A-group	0.9490	0.9491	0.0012	0.9468–0.9513
	B-group	0.9565	0.9565	0.0011	0.9544–0.9585
95.0	A-group	0.9622	0.9622	0.0008	0.9606–0.9636
	B-group	0.9658	0.9658	0.0010	0.9639–0.9677
99.0	A-group	0.9780	0.9780	0.0005	0.9772–0.9790
	B-group	0.9786	0.9786	0.0007	0.9769–0.9799
99.9	A-group	0.9879	0.9879	0.0003	0.9873–0.9883
	B-group	0.9871	0.9874	0.0007	0.9856–0.9880

The table demonstrates the high stability of the thresholds. For all percentiles considered, the mean values across subsamples are virtually identical to the thresholds obtained from the full sample. Standard deviations are extremely small: for Group A, they range from 0.0010 to 0.0018, and for Group B, from 0.0002 to 0.0006. Confidence intervals are also very narrow – for example, for the 80th percentile of Group A, the 95% CI is 0.8766–0.8835. Such high reproducibility under variation in subsample composition allows the calculated thresholds to be regarded as reliable and suitable for use in analyzing new ceramic collections, including archaeological ones.

4.2.2. Threshold validation (test sample)

4.2.2.1. Kick wheel pottery.

The procedure for validating threshold values for the second analytical approach is entirely analogous to that described in Section 4.1.2.1. In the test sample of 214 vessels made by eight potters on kick wheels, integral similarity measures were calculated for each pair: SA (the mean across the 12 most informative points in Group A) and SB (the mean across the 34 points in Group B). A pair was considered to have passed the threshold if both SA ≥ TA and SB ≥ TB, where TA and TB are threshold values corresponding to a given percentile of the between-class distributions in the main sample (see Table 9).

To assess the stability of the results across sample sizes, repeated subsampling without replacement was used (1000 iterations) for n = 30, 80, 130, and 180 vessels. For each strictness level, we recorded

mean accuracy (the share of true pairs among those passing the threshold) and the mean number of such pairs, together with their 95% confidence intervals.

The results (Table 11) reveal the same pattern as in the first method: increasing threshold strictness raises accuracy but reduces the number of identified pairs. At low thresholds (80th–85th percentiles), the number of passing pairs is maximal (from 2363 to 3297), but accuracy remains low – around 30–34%. This means that roughly two-thirds of the pairs satisfying the criterion actually belong to different potters, making such thresholds unsuitable for our purpose.

Table 11
Validation of curvature thresholds on kick wheel pottery

Percentile	Sample size	Median identification accuracy (%)	Std. dev. (proportion), %	95% CI (accuracy)	Median number of pairs	Std. dev. (pairs)	95% CI (pairs)
80	30.0	29.7	7.2	18.7–46.0	86	18.4	61–128
	80.0	29.9	3.2	24.3–36.9	643	65.8	532–788
	130.0	29.9	2.0	26.6–34.0	1710	103.9	1518–1918
	180.0	30.0	1.0	28.2–32.1	3297	107.9	3093–3501
85	30.0	34.3	8.3	20.7–53.5	62	14.1	41–96
	80.0	34.2	3.6	28.1–42.1	461	49.8	377–573
	130.0	34.1	2.1	30.5–38.7	1233	79.8	1083–1386
	180.0	34.2	1.2	32.2–36.7	2363	85.3	2205–2537
90	30.0	42.1	10.6	25.0–65.2	41	9.9	25–66
	80.0	42.0	4.3	34.8–51.2	301	33.6	244–375
	130.0	42.0	2.6	37.2–47.3	803	58.9	698–926
	180.0	42.0	1.4	39.5–44.9	1540	55.3	1435–1645
95	30.0	55.0	14.6	29.4–84.6	19	5.7	10–32
	80.0	54.7	6.2	43.3–67.2	138	18.4	106–180
	130.0	54.7	3.5	48.3–62.0	366	28.6	315–427
	180.0	54.6	1.9	51.3–58.5	706	28.5	654–761
99	30.0	75.0	33.3	0.0–100.0	3	1.9	0–8
	80.0	73.3	10.3	52.6–92.0	22	4.7	14–32
	130.0	73.5	5.7	62.3–84.3	60	6.9	47–74

Percentile	Sample size	Median identification accuracy (%)	Std. dev. (proportion), %	95% CI (accuracy)	Median number of pairs	Std. dev. (pairs)	95% CI (pairs)
	180.0	72.9	2.8	67.8–78.6	115	6.6	102–128
99.9	30.0	0.0	31.0	0.0–100.0	0	0.3	0–1
	80.0	50.0	48.3	0.0–100.0	1	0.9	0–3
	130.0	100.0	31.1	0.0–100.0	2	1.2	0–4
	180.0	80.0	13.4	66.7–100.0	4	1.1	2–6

When strictness is increased to the 90th and 95th percentiles, accuracy rises to 41% and 53%, respectively, while the number of pairs decreases to 1668 and 771. At the 99th percentile, accuracy reaches 73.7% (95% CI: 68.3–78.9%), and the mean number of pairs passing the threshold is 128 (95% CI: 115–141). Further tightening of the criterion to the 99.9th percentile provides a modest gain in accuracy (up to 83.9%), but at the cost of a drastic reduction in the number of pairs to 4–5, which makes this level practically useless for analyzing real archaeological collections, especially since smaller samples (30–80 vessels) often yield zero pairs.

Accordingly, for kick wheel pottery, the optimal balance between accuracy and the number of diagnostically useful pairs in the second analytical approach is also provided by the threshold corresponding to the 99th percentile of the between-class distributions in the main sample, just as in the first method. In the test sample, this threshold yields an average of about 73% true same-potter pairs, and the number of pairs (115 for a sample of 180 vessels) is possibly sufficient for meaningful interpretation. Examples of some vessel pairs correctly identified as products of the same potter are shown in Fig. 10; examples of «misclassified» pairs are shown in Fig. 11.

4.2.2.2. Hand-operated wheel

The analysis was carried out on a sample of 78 vessels made by four potters. The largest number of diagnostically useful pairs (132) is obtained at the 80th percentile threshold, with an accuracy of 76.4% (Table 12). Increasing strictness to the 85th percentile hardly changes accuracy (77.6%) but reduces the number of pairs to 95. Further increases to the 90th and 95th percentiles bring accuracy to 81.8% and 77.6%, respectively, while the number of pairs drops to 54 and 32. At the 99th percentile, accuracy reaches 77.0%, but only 1 pair remains, which is too few for practical use. The 99.9th percentile is not acceptable for hand-operated wheel pottery.

Table 12
Validation of curvature thresholds on hand-operated wheel pottery

Percentile	Sample size	Median identification accuracy (%)	Std. dev. (proportion), %	95% CI (accuracy)	Median number of pairs	Std. dev. (pairs)	95% CI (pairs)
80	30	77.4	10.3	57.1–95.8	23	6.0	14–37
	50	76.5	5.4	66.7–87.0	66	9.4	49–87
	70	76.4	2.5	73.3–83.5	132	8.1	117–148
85	30	78.6	11.6	55.6–100.0	17	5.1	9–28
	50	77.6	6.6	66.7–91.7	48	8.1	34–65
	70	77.6	2.8	74.2–85.4	95	7.0	82–108
90	30	81.3	14.7	50.0–100.0	10	3.8	4–19
	50	78.6	8.1	65.0–95.8	28	5.6	18–40
	70	77.6	3.4	73.7–87.5	57	4.8	46–64
95	30	83.3	26.4	0.0–100.0	4	2.1	1–9
	50	76.9	13.0	55.6–100.0	11	3.0	5–17
	70	76.0	5.4	70.0–88.9	21	2.6	15–25
99	30	0.0	48.4	0.0–100.0	0	0.6	0–2
	50	100.0	41.2	0.0–100.0	1	0.8	0–3
	70	100.0	7.1	100.0–100.0	3	0.7	1–3
99.9	30	0.0	0.0	0.0–0.0	0	0.0	0–0
	50	0.0	0.0	0.0–0.0	0	0.0	0–0
	70	0.0	0.0	0.0–0.0	0	0.0	0–0

Thus, for hand-operated wheel pottery, the optimal strictness level in the second analytical approach, as in the first, is the 80th percentile of the between-class distributions in the main sample. At this threshold, approximately 77% of the identified pairs in the test sample are indeed made by the same potter, and the number of pairs (around 140 for a 70-vessel subsample) is sufficient for drawing defensible conclusions. This result confirms the robustness of the proposed method and its applicability to pottery with different degrees of technological standardization.

5. Discussion

Despite the different nature of the two procedures used to derive criteria for identifying the same potter, their results are highly consistent. In both cases, the optimal threshold for highly standardized kick wheel pottery corresponded to the 99th percentile of the between-class distributions. For the less standardized hand-operated wheel pottery, the optimal threshold in both approaches was the 80th percentile.

Such convergence is unlikely to be accidental. It suggests that both approaches capture the same underlying structure in the data – the balance between within-group and between-group variability characteristic of a single potter's products. Although the key-point method operates with integral characteristics of vessel parts (inclination angles and proportions), whereas the curvature method works directly with the shape of the vessel profile, both methods are sensitive to the same fundamental regularities in ceramic manufacture.

A particularly interesting question is whether both methods identify the same pairs of vessels or different ones. To determine how consistent the results of the two morphometric approaches are, the pair lists obtained at the optimal thresholds established in Section 4 were compared. The comparison was made using the full test samples without subsampling, after normalizing the records and converting the pairs to unordered form.

The results for the kick wheel vessels are as follows. The key-point method identified 54 unique pairs, while the curvature method identified 163. The intersection of the two sets was 4 pairs. If the four pairs identified by both methods are removed from each set, the proportion of pairs unique to the first method is about 92.6%, and to the second method about 97.5% (Table 13).

The results for the hand-operated wheel vessels are as follows. The key-point method identified 140 unique pairs, and the curvature method 164 pairs. The intersection of the two sets was 40 pairs. Following the same simple principle, the proportion of pairs unique to the first and second methods is 71.4% and 75.6%, respectively (Table 14).

Table 13
Overlap between pair sets identified by the key-point and curvature methods on kick-wheel pottery

Methods and conditions	Pairs detected
Pairs detected by the key-point method	54
Pairs detected by the curvature method	163
Pairs detected by both methods	4
Unique pairs detected by the key-point method	50 (92.6%)
Unique pairs detected by the curvature method	159 (97.5%)

Table 14
Overlap between pair sets identified by the key-point and curvature methods on hand-operated wheel pottery

Methods and conditions	Pairs detected
Pairs detected by the key-point method	140
Pairs detected by the curvature method	164
Pairs detected by both methods	40
Unique pairs detected by the key-point method	100 (71.4%)
Unique pairs detected by the curvature method	124 (75.6%)

In both cases, the overlap between the sets is small, though noticeably larger for the hand-operated wheel. This may reflect greater within-group variability in hand-operated wheel forms: vessels made by the same potter vary more strongly, and both methods, operating with more diffuse clusters, are more likely to converge on the same pairs.

Low overlap does not indicate contradiction; on the contrary, it confirms complementarity. A potter's individual signature is multidimensional: the same potter may show high stability in some parameters and substantial variability in others. Accordingly, vessels that are close in proportional structure do not necessarily match in curvature, and vice versa. This is why the pair sets identified by the two methods overlap only partially. There is yet another important reason why each method identifies different pairs of potters. In seeking to minimize false positives, we deliberately exclude the «genuine» pairs made by a single potter. This point is well illustrated by the TPR results (Tables 4 and 9). Thus, there is always a chance that a vessel pair rejected by one method as insufficiently similar to the products of the same potter will be accepted by the other. In this sense, the final set of identified pairs always reflects the specific threshold structure of each method.

This leads to an important methodological conclusion: neither approach is universal on its own. Their combined use allows different aspects of morphological variability to be captured and strengthens the reliability of identifying vessels made by the same potter. In archaeological practice, therefore, the optimal strategy is to combine the two morphometric approaches.

6. Archaeological test

To test the proposed methods, we selected the Roman-period cemetery of Frontovoe 3 in southwestern Crimea. The site has been completely excavated and contains a representative ceramic assemblage (Sviridov and Yazikov 2023; 2024a; 2024b). The largest ceramic group here is imported red-slip ware, amounting to 383 specimens. The imported character of this pottery limits our ability to identify particular potters and to study networks between artisans and consumers. Instead, we focus on a different question that is not contradicted by the imported character of the vessels: assessing the chronological compactness of graves containing pottery from a same production unit. If the vessels

were made by potters with the same, or very similar, technical skills, we may reasonably expect them to occupy a close chronological position, with that shared position reflected in the archaeological record.

The vessels were prepared according to the same principles as the ethnographic collections. In the key-point method, vessels were first divided into groups according to their construction type (the number of analytical parts identified). Within each group, integral SA values were calculated as the mean similarity of proportional characteristics of all vessel's parts and inclination angles of the «upper» parts (neck or cheek) and SB values as the mean similarity of the inclination angles of the «lower» vessel's parts. The assignment of features to Groups A and B was the same as in the ethnographic series. Because the archaeological pottery is comparable in its level of standardization to hand-operated wheel products, thresholds corresponding to the 80th percentile were used for both methods.

The key-point analysis identified 259 vessel pairs meeting the criteria above. The curvature method identified 193 such pairs. Comparison of the pair lists obtained by the two methods revealed an interesting pattern. As in the ethnographic case, the lists differ substantially. The proportion of unique pairs in the key-point list was 94.2% (244 pairs), and in the profile-curvature list 92.2% (178 pairs). The number of pairs identified by both methods was 15 (Fig. 14). This is further evidence that each method captures different aspects of potters' skill in shaping vessels.

A key objective of the analysis of the Frontovoe 3 pottery was to determine how vessel links attributed by our method to the same production unit are distributed in time, and how closely the graves containing such vessels are dated. To this end, several steps were taken. First, a combined list was compiled from the pair lists generated by each method. The 15 pairs identified by both methods were counted only once. On the basis of this combined list, a network graph was built in Gephi using the ForceAtlas 2 layout algorithm (Fig. 12) (Jacomy et al. 2014). Each node in the graph represents a grave, and each edge represents the presence in those graves of vessels classified as products of the same production unit.

To identify objectively the groups of graves most closely connected by vessels from shared production units, we applied the Leiden clustering algorithm (Traag et al. 2019). This algorithm belongs to the family of modularity-maximization methods, which assess the density of internal connections in a community relative to random expectation. Unlike the widely used Louvain algorithm, Leiden has several advantages: it yields more stable partitions, avoids disconnected communities, and offers better guarantees of convergence. These properties make it particularly suitable for analyzing the network of links between graves.

Application of the Leiden algorithm identified 11 communities in the graph, shown in different colors in Fig. 12. Besides, we colored the nodes according to the already established dating of the graves based on metal and glass finds (Fig. 13) (Gavritukhin et al. 2021). This procedure showed good chronological coherence across most of the larger communities identified by Leiden. Of particular interest are the communities marked in Fig. 12 as A, B, C, D, E, and F. Communities A, B, and C consist mainly of graves belonging to the early phase of the necropolis, periods 1 and 2 (Fig. 13: 1, 2), that is, the late 1st to 2nd centuries AD. Communities D and E form the core of the graph, with the densest connections and the

majority of graves. These two communities consist almost entirely of graves dating to period 3, the late 2nd to first half of the 3rd century AD (Fig. 13: 3). Finally, community F, the most distant of all on the graph, is also the latest: it consists entirely of burials from period 4, the second half and late 3rd to 4th centuries AD (Fig. 13: 4).

Statistical analysis of the chronological distribution of links between graves based on vessels from the same production unit yields revealing results (Table 15). In 61.3% of cases, such links were established between complexes belonging to the same chronological period. In 25.8% the links were established between complexes belonging to neighboring periods. Only 12.9% of links connect graves from more distant periods. This pattern suggests that vessels produced by the same production unit circulated for a limited time and that similarities in vessel forms may be useful not only for typological classification but also for relative chronological assessment.

Table 15
Distribution of links by chronological proximity

Type of link	**Quantity**	**%**
Within a period	257	61.3
Between neighboring periods	108	25.8
Across 1 period	50	11.9
Across 2 periods	4	1.0

7. Conclusion

The study shows that the identification of vessels made by the same potter, or by the same production unit, can be approached through a quantitatively defined threshold of morphological similarity, beyond which further subdivision of ceramic classification ceases to add analytical value. In this sense, the proposed procedures do not replace typology; rather, they make typological reasoning more explicit, more reproducible, and more firmly grounded in observable variation in vessel form.

Validation on ethnographic and experimental material demonstrates that both morphometric procedures are capable of identifying same-potter products with a practically useful degree of accuracy. In the key-point method, accuracy reaches about 77.6% for kick wheel pottery and about 79.5% for hand-operated wheel pottery at the selected thresholds; in the curvature method, the corresponding figures are about 73.7% for kick wheel pottery and about 76–77.6% for hand-operated wheel pottery, depending on the threshold and sample size. These results are not perfect, but they are sufficiently robust to support archaeological inference, especially given that the test material was deliberately selected to be difficult to distinguish visually.

The two procedures should not be treated as interchangeable, nor should one be ranked as inherently superior to the other. Their overlap is limited, which indicates that each captures a different aspect of

morphological variability. Taken together, they provide a more reliable basis for identifying production-related similarity than either method alone. The methodological value of the study therefore lies not in forcing a single universal criterion, but in showing how complementary measurements can be combined within a reproducible analytical framework.

Application to the Frontovoe 3 cemetery further suggests that morphologically linked vessels tend to cluster close in time. This pattern supports the view that vessels from the same production unit had a limited circulation span and that ceramic similarity may serve as an auxiliary indicator of relative chronology.

Several limitations should be acknowledged. First, both methods are currently designed for the analysis of complete vessel forms; extending them to fragmented material will require a separate study aimed at recalibrating threshold values on the basis of partial contours. Second, the methods were tested on pottery produced on pottery wheels and may not transfer directly to all ceramic technologies without preliminary validation.

In broader theoretical terms, the study shows that archaeological typology can be substantially strengthened by moving from intuitive division of forms toward a quantitatively grounded assessment of morphological similarity. Such an approach does not replace cultural-historical interpretation but makes it more transparent and reproducible. In this sense, the proposed method is a step toward an archaeology in which classification not only orders material but also becomes a tool for reconstructing real production relationships associated with apprenticeship, skill transmission, and the persistence of craft traditions.

Declarations

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Author Contribution

E.S. wrote the main manuscript text and prepared figures.

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Data Availability

All supplementary materials are available on OSF: https://doi.org/10.17605/OSF.IO/5W6T9

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Footnotes

1. This value is arbitrary; any other could have been chosen.
2. Points 1 and 51 are not considered, as their similarity is always 1.