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GEOMETRIC MORPHOMETRIC DIVERSITY OF BRONZE AXES FROM THE LUSATIAN URNFIELD CULTURES HOARD FROM ROSKO (NORTH GREATER POLAND)

ABSTRACT

Pawlina A., Hałuszko A. and Maciejewski M. 2025. Geometric morphometric diversity of bronze axes from the Lusatian Urnfield cultures hoard from Rosko (north Greater Poland). *Sprawozdania Archeologiczne* 77/1, 267-284.

The hoard from Rosko (Site 47, Wielkopolskie Voivodeship, Czarnków-Trzcianka district) contained at least 71 bronze artefacts, mainly socketed axes, and is dated to HaB2-HaB3. This study focuses on analysing the shape of the axes, evaluating their morphological differenc Geometric morphometric diversity of bronze axes from the Lusatian Urnfield cultures hoard from Rosko (north Greater Poland) Afiliacja Haluszkoes, and assigning these artefacts to the currently accepted typological classification by Kuśnierz. Absolute measurements and photographic documentation were required for geometric morphometric method (GMM) analyses, conducted on 66 axes. A key objective of the study was to compare the outcomes of GMM analyses using the landmark and outline methods. The results revealed intra-typological differences among the Czarków type axes, variant C, suggesting that the casts were likely made using more than one mould. Variations in shape, production techniques, and usage indicated that the axes could not be unanimously traced back to a single casting mould.

Keywords: hoards, Bronze Age, Lusatian Urnfield cultures, geometric-morphometric method, socketed axes
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INTRODUCTION

The conventional approach to describing archaeological artefacts and establishing their typologies is based on factors such as length, width, angles and shape in general (*e.g.*, oval, triangular) (Wilczek 2017, 19). Such classifications, however, are often subjective and inconsistent, with feature descriptions remaining vague. The geometric morphometric method (GMM) was initially developed in the biological sciences (Brandt *et al.* 2023). It involves analysing shape variables and processing these data (Slice 2005, 5) using either two-dimensional or three-dimensional input. Statistical procedures for testing and visualising shape differences (Rohlf and Marcus 1993, 129) offer insights distinct from those derived through absolute measurements. GMM should not replace typology but serve as a tool to test typological findings in specific cases.

The current classification of socketed axes is based on typological analyses of approximately 900 bronze items discovered within modern-day Poland (Kuśnierz 1998). In his work, Kuśnierz highlights subtle differences in collar height between the Czarków and Przedmieście type axes, illustrating the challenge of distinguishing between types with only minor variations. Key features enabling differentiation include the shape of the cutting edge, the width of the socket mouth, and the shape (Dąbrowski 1968, 35; Kaczmarek 2002, 96). Kuśnierz's (1998) classification also considers variant-specific characteristics, such as the ornamentation of these artefacts. The Przedmieście type axes, for instance, are divided into eight variants (A–H) based on this criterion, *i.e.* features like straight or fan-shaped groove arrangement (Kuśnierz 1998, 48, 49).

This study aimed to determine whether 2D GMM analysis enables the identification of inter- and intra-typological variation in the Rosko axes. Key features of these axes, including the cutting edge, loop, and socket mouth, were closely examined to assess any significant morphological differences. Additionally, the study sought to identify which axes were most similar to each other, potentially indicating production from the same casting mould. It also explored whether variations in the shapes of the cutting edges could result from the use of the axes. The largest groups of axes, the Czarków type, variant C, and the Przedmieście type, variant E, were analysed to determine if any other distinctions beyond collar height and grooved decoration could be used to differentiate these two types. Another research objective was to assess the comparability of results obtained through different 2D GMM analysis methods, specifically the landmark and outline approaches. The Rosko hoard was chosen for study due to the large number of similar and metrically consistent artefacts found within a single assemblage.

MATERIALS AND METHODS

The starting point for the 2D GMM analyses was the measurement and photographic documentation of axes held in the Stanisław Staszic Regional Museum's collection in Piła. Typological classification was based on the monograph of the assemblage (Machajewski and Maciejewski 2006). A total of 66 axes were published, which belong to: Czarków type, variant C (44 pcs), Czarków type referring to variant B (1 pc.), Czarków type, variant K (1 pc.), Kopaniewo type , variant A (1 pc.), Przedmieście type, variant D (1 pc.), Przedmieście type, variant E (17 pcs) and an axe with a heavily reduced cutting edge and richly decorated sides, variant A (*Tüllenbeile mit reich verzierten Breitseiten*; 1 pc.; similar artefacts are named differently in the various volumes of the *Prähistorische Bronzefunde* series: *e.g., Tüllenbeile mit öse und reicher leisteverzierung* in the case of Slovakia (Novotná 1970), *Tüllenbeile mit winkel- oderbogenverzierrung* in the publication of axes from Austria (Mayer 1977), for Hungary a complete typological division of this type of artefact has not yet been proposed) (Fig. 1). The styles of the individual axe types indicated their provenance from various regions of Central Europe, but most are typical in Greater Poland and Silesia (Machajewski and Maciejewski 2006, 143).

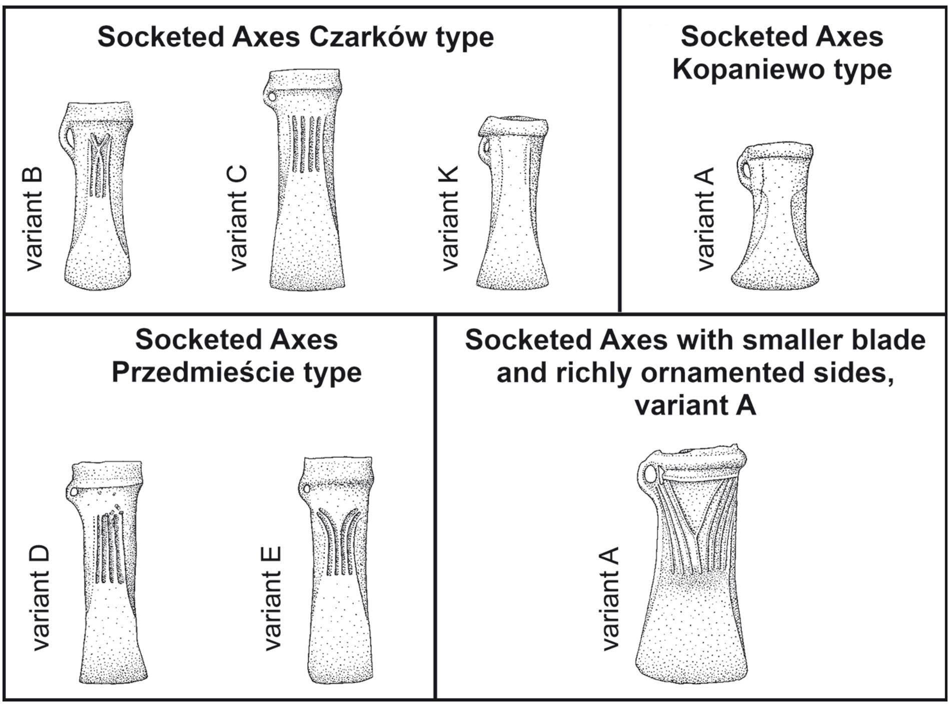

Fig. 1. Types and variants of Rosko axes included in the 2D GMM analysis (drawing by J. Kędelska; graphic editing by A. Pawlina)

Before conducting the 2D GMM analyses, all axes were measured with digital calliper to an accuracy of 0.02 mm. The measurements included the length and widths at various points along the axes. A total of 11 measurements were taken: the most excellent axe length (H), top width (S1), bottom width (S2), socket width (S3), width above the loop (S4), the section from the outermost part of the loop (S5), below the loop (S6), above the ornament (S7), the smallest axe width (S9), below the ornament/ribs (S8) and cutting-edge width (S10) (Fig. 2). Variations in absolute measurements and indices were statistically analysed for the most numerous axe types: Czarków type, variant C, and Przedmieście type, variant E. The nonparametric Mann-Whitney U test for two independent samples was used in the study. Single specimens represented the remaining axe types and were therefore excluded from these statistical analyses.

Only complete axes and those without significant damage were subjected to 2D GMM analysis, as their preservation status could affect the results. Three axes were excluded from further study due to their poor state of preservation: two of the Czarków type, variant C, and one of the Przedmieście type, variant E. These artefacts were the most damaged and incomplete. Following these exclusions, 63 axes were selected for analysis. The analyses employed both the landmark and outline methods, based on photographic documentation of the artefacts.

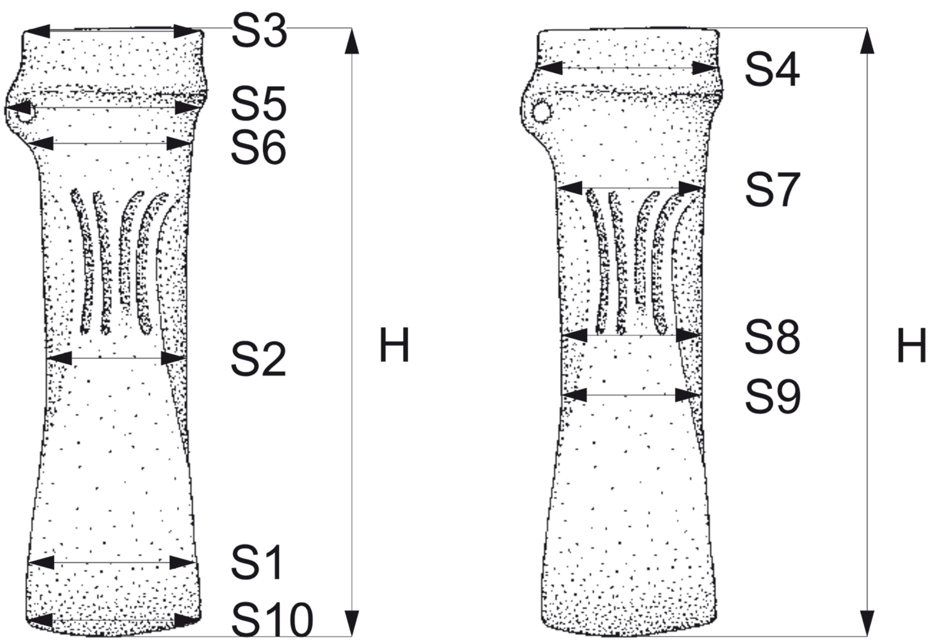

Fig. 2. Schematic representation of the applied absolute measurement method (drawing by J. Kędelska; graphic editing by A. Pawlina)

Fig. 3. Landmark configuration on Rosko axes used in the 2D GMM analysis (photo by M. Maciejewski; graphic editing by A. Pawlina)

Table 1. Landmark number 7. Description Central point at the top of the flange, located along the vertical axis of the axe, corresponding to their arrangement in Fig. 3

Landmark number	Description
1	Central point on the distal (cutting) edge of the blade, located at its midpoint. Serves as the primary reference for symmetry and as the starting point for outline-based shape analysis.
2,13	Lateral extremities of the cutting edge, marking the sharp tips of the blade. Define the maximum transverse extent of the edge.
3,12	Narrowest lateral points on the blade body, corresponding to the minimal width of the axe. These points reflect the medial constriction of the implement.
4	Point located directly below the socket loop, at the junction between the loop and the axe body. Marks the lower attachment of the loop.
5	Lateral-most point on the outer margin of the socket loop. Indicates the maximum projection of the loop from the axe body.
6,9	Upper lateral margins of the socket rim, corresponding to the widest part of the socket opening. Delimit the transverse extent of the mouth.
8	Central point at the base of the flange, positioned along the vertical axis of the axe. Defines the deepest part of the socket transition.
10	Lateral extremity of the flange's outermost contour, indicating the maximal outward projection of the flange.
11	Inferior point on the flange margin, located below point 10. Marks the lower termination of the flange.

The first step in the 2D GMM process involved digitally aligning the axes with respect to their axis of symmetry, with the cutting edge positioned downward and the loop on the left, following the standard methodology for 2D GMM (Serwatka 2020, 224; Wiśniewski *et al.* 2015, 13). The images were then converted into TPS files, and landmarks and outlines were applied using the open-access software TpsUtil and TpsDig2 (Rohlf 2021; 2022). A total of 13 landmarks were identified at characteristic points on all studied objects (Fig. 3, Table 1). These landmarks were selected based on their ease of localisation, consistent presence, and unambiguous placement across all axes. According to established guidelines in geometric morphometrics, landmarks should be homologous, reliably identifiable, and provide adequate coverage of the object's morphology (Bookstein 1997; Cardillo 2010).

Additionally, an outline of 100 points was created, starting from a point at the centre of the cutting edge. The raw data were further analysed statistically in the PAST programme (Hammer *et al.* 2001), beginning with a Procrustes transformation relative to the principal axis (Adams *et al.* 2004, 14,15; Serwatka 2020). This transformation standardised the sizes of the objects (Figs. 4 and 5), allowing for a comparative analysis of their shapes (Cooke and Terhune 2015, 6; Masojć *et al.* 2020, 27-32; Serwatka 2020, 225; Wiśniewski *et al.* 2015, 13). The final step in the process was to perform a principal component analysis (PCA).

All measurements and landmark points used for GMM analyses have been made publicly available on the Zenodo platform under DOI 10.5281/zenodo.16634500.

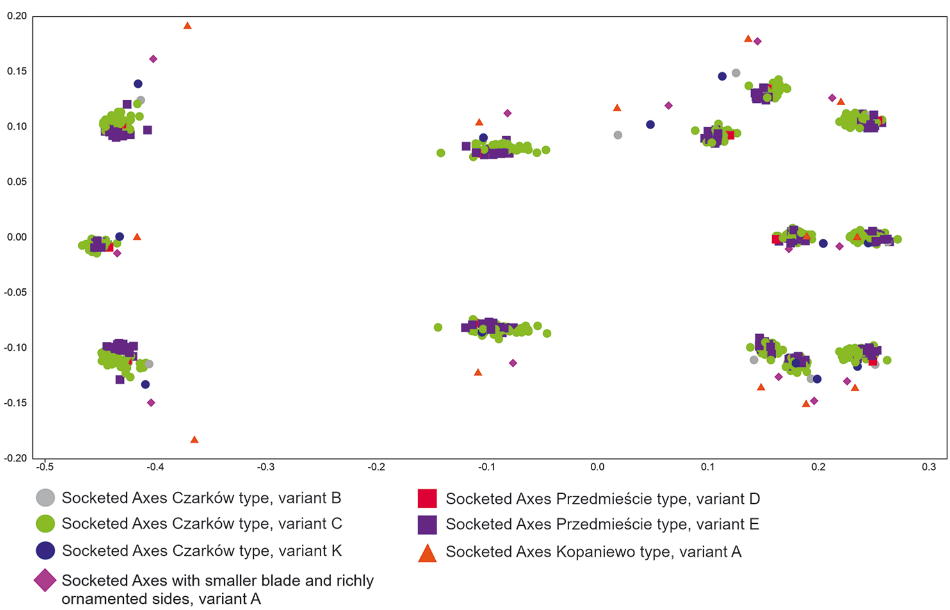

Fig. 4. Data processed by the landmark method after applying Procrustes transformation

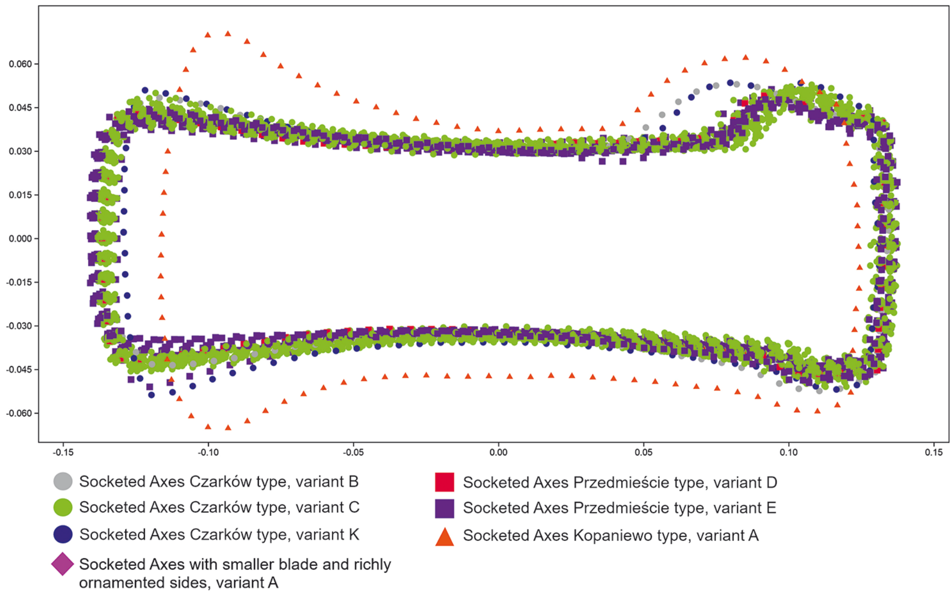

Fig. 5. Data processed using the outline method following Procrustes transformation

RESULTS

The tables summarising the absolute measurements for the Czarków type, variant C, and the Przedmieście type, variant E, indicate that the most significant differences in mean values between the two groups pertain to the S10 measurement, *i.e.* the cutting edge width (Table 2). Some standard deviation values are notably high. The highest standard deviation is observed for the height parameter (sd = 5.63 mm) in the Czarków type axes, variant C. At the same time, a lower value for the exact measurement is recorded for the Przedmieście type axes, variant E (sd = 3.32 mm). In addition to the height parameter, the standard deviation for S10 is high in both groups. The data show that, for most measurements, standard deviation values are lower for the Przedmieście type axes, variant E. However, exceptions include measurements S5 and S10, where the values are lower for the Czarków type, variant C. Regarding the median, the most significant differences between the two types are observed for measurements H, S2, S5, and S10. The highest values for measurements S1-S10 are found in the Czarków type axes, variant C, while the Przedmieście type axes, variant E, have higher results than the Czarków type only in the measurement of axe length. For width and length indices, the averages are consistently higher for the Czarków type axes, variant C (Table 3). Most standard deviation values are also higher for the Czarków type, variant C, except for the S2/H and S10/H indices. Notably, the highest standard deviation values are observed for S3/H (4.25 mm) and S4/H

Table 2. Absolute measurements [mm] for axes of the Czarków type, variant C, and the Przedmieście type, variant E. Abbreviations: n – number of observations; M – mean; sd – standard deviation; Me – median; min – minimum value; max – maximum value

Measured dimensions											
Czarków type, variant C											
	H	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
n	44	44	43	44	44	44	44	44	44	44	43
M	98.54	24.30	29.94	30.75	33.21	33.55	26.97	26.36	24.03	23.83	31.46
sd	5.63	0.58	0.92	1.32	1.29	1.12	0.85	0.85	1.52	0.74	1.55
Me	99.05	24.24	29.86	30.58	33.27	33.41	26.91	26.38	23.94	23.97	31.62
min	65.45	23.10	27.93	28.54	28.42	31.96	25.50	24.94	22.02	22.12	23.74
max	106.39	25.55	31.97	38.06	38.64	38.30	30.05	29.68	32.71	25.20	34.33
Przedmieście type, variant E											
	H	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
n	17	17	17	16	16	17	17	17	17	17	17
M	99.79	23.58	28.64	30.00	32.14	31.82	26.51	25.40	23.05	23.13	28.85
sd	3.32	0.52	0.78	0.37	0.45	1.89	0.64	0.61	0.43	0.39	1.86
Me	100.69	23.61	28.42	30.01	32.18	32.10	26.78	25.33	23.09	23.12	28.69
min	88.09	22.14	27.85	29.44	31.33	24.92	25.48	24.50	21.99	22.55	26.21
max	102.30	24.68	30.80	30.60	32.82	33.40	27.42	26.44	24.08	24.01	34.56

Table 3. Proportional indices of width and length for socketed axes of the Czarków type, variant C and the Przedmieście type, variant E. Abbreviations: n – number of observations; M – mean; sd – standard deviation; Me – median; min – minimum value; max – maximum value

Width and length indices										
Czarków type, variant C										
	S1/H	S2/H	S3/H	S4/H	S5/H	S6/H	S7/H	S8/H	S9/H	S10/H
n	44	43	44	44	44	44	44	44	44	43
M	24.76	30.16	31.43	33.92	34.25	27.53	26.91	24.47	24.27	31.99
sd	1.90	1.00	4.25	4.09	3.87	2.97	2.99	2.21	1.71	1.51
Me	24.51	29.95	30.84	33.61	33.73	27.04	26.45	24.08	24.11	31.87
min	22.99	28.40	28.27	28.38	31.97	25.15	24.63	22.01	21.77	29.27
max	36.03	32.73	58.15	59.04	58.52	45.92	45.35	34.31	34.07	36.27
Przedmieście type, variant E										
	S1/H	S2/H	S3/H	S4/H	S5/H	S6/H	S7/H	S8/H	S9/H	S10/H
n	17	17	16	16	17	17	17	17	17	17
M	23.64	28.76	29.85	31.98	31.87	26.59	25.48	23.12	23.21	28.98
sd	0.75	1.79	0.61	0.74	1.30	1.14	1.08	0.79	0.89	2.68
Me	23.50	28.16	29.69	31.86	31.85	26.57	25.23	22.98	22.97	28.47
min	22.84	27.53	28.97	30.83	28.29	25.10	24.43	22.11	22.22	26.04
max	25.76	34.45	31.84	34.24	34.47	29.87	28.39	25.14	25.59	36.08

(4.09 mm) in the Czarków type axes. Median values, too, are generally higher for the Czarków type, variant C.

For the absolute measurements, as well as the width and length indices for the Czarków type axes, variant C, and the Przedmieście type axes, variant E, a non-parametric Mann-Whitney U test was conducted for two independent samples (Tables 4 and 5), as only these artefacts were represented by more than one specimen. No significant statistical differences were observed only for absolute measurements for H and S6 (Table 4). For width and length indices, all differences were statistically significant. However, it is essential to interpret the statistically significant results in the context of the low and varied sample sizes, as well as the typologically significant variations in the absolute measurements of the two axe types.

The PCA performed on the data collected using landmarks produced a total of 26 principal components (PCs), with the first four PCs accounting for 90% of the variance (Table 6). The first two PCs described the majority of the variance (75.55%). A graph was generated for the data after the Procrustes transformation, on which all test objects substantially overlay each other (Fig. 4). The analysis highlights that particular axes stand out due to their distinct shapes: the Kopaniewo type, variant A, the axe with a significantly reduced cutting edge and richly decorated sides, variant A, and the Czarków type, variant K. These axes exhibit greater variance compared to other types, as indicated by their positions on the graph, appearing as outlier points spread out from other objects. The remaining axes form clusters at the designated landmarks, represented by the Czarków type, variant C and the Przedmieście type, variants E and D, whose variances are similar to each other. Significant differences are observed between the studied objects in specific elements, including the cutting edge, the socket mouth area, and the loops.

The PCA results obtained using the landmark method show that the majority of the Czarków type axes, variant C, and the Przedmieście type axes, variant E, are distributed along the axis of the second principal component (Fig. 6). Specimens located in the area of positive PC1 and negative PC2 values stand out from the other bronzes in this deposit. These include the axe with a strongly reduced cutting edge and richly decorated sides, variant A; the Czarków type axes, variants K and B; and the Kopaniewo type axe, variant A. A broader cutting edge, loop, or socket mouth characterises these specimens. This graph section also contains three Czarków type axes, variant C, and one Przedmieście type axe, variant E. The majority of Czarków type axes, variant C, are distributed along negative PC2 and positive PC1 values, as well as along positive values for both components. In contrast, most Przedmieście type axes, variant E, are positioned within the negative PC1 and positive PC2 value ranges. Additionally, the point representing the Przedmieście type axe, variant D, is located along the positive values of the PC2 axis.

PCA of the data collected using the outline method generated a total of 60 PCs, with the first four accounting for 90% of the variance (Table 7). The first two PCs filled 80.656% of the variance, prompting further analyses to focus exclusively on these components. The

Table 4. Non-parametric Mann-Whitney U test for absolute measurements of Czarków type, variant C axes (n=44) and Przedmieście type, variant E axes (n=17)

	Width and length indices									
	S1/H	S2/H	S3/H	S4/H	S5/H	S6/H	S7/H	S8/H	S9/H	S10/H
U-Mann-Whitney	3.8447	4.3032	3.8369	4.3274	4.7295	2.1475	3.6357	3.9013	3.7805	4.3514
p-value	0.000121	1.68E-05	0.000125	1.51E-05	2.25E-06	0.031752	0.000277	9.57E-05	0.000157	1.35E-05

Table 5. Non-parametric Mann-Whitney U test for width and length indices of Czarków type axes, variant C (n=44) and Przedmieście type, variant E axes (n=17)

	Width and length indices									
	S1/H	S2/H	S3/H	S4/H	S5/H	S6/H	S7/H	S8/H	S9/H	S10/H
U-Mann-Whitney	3.8447	4.3032	3.8369	4.3274	4.7295	2.1475	3.6357	3.9013	3.7805	4.3514
p-value	0.000121	1.68E-05	0.000125	1.51E-05	2.25E-06	0.031752	0.000277	9.57E-05	0.000157	1.35E-05

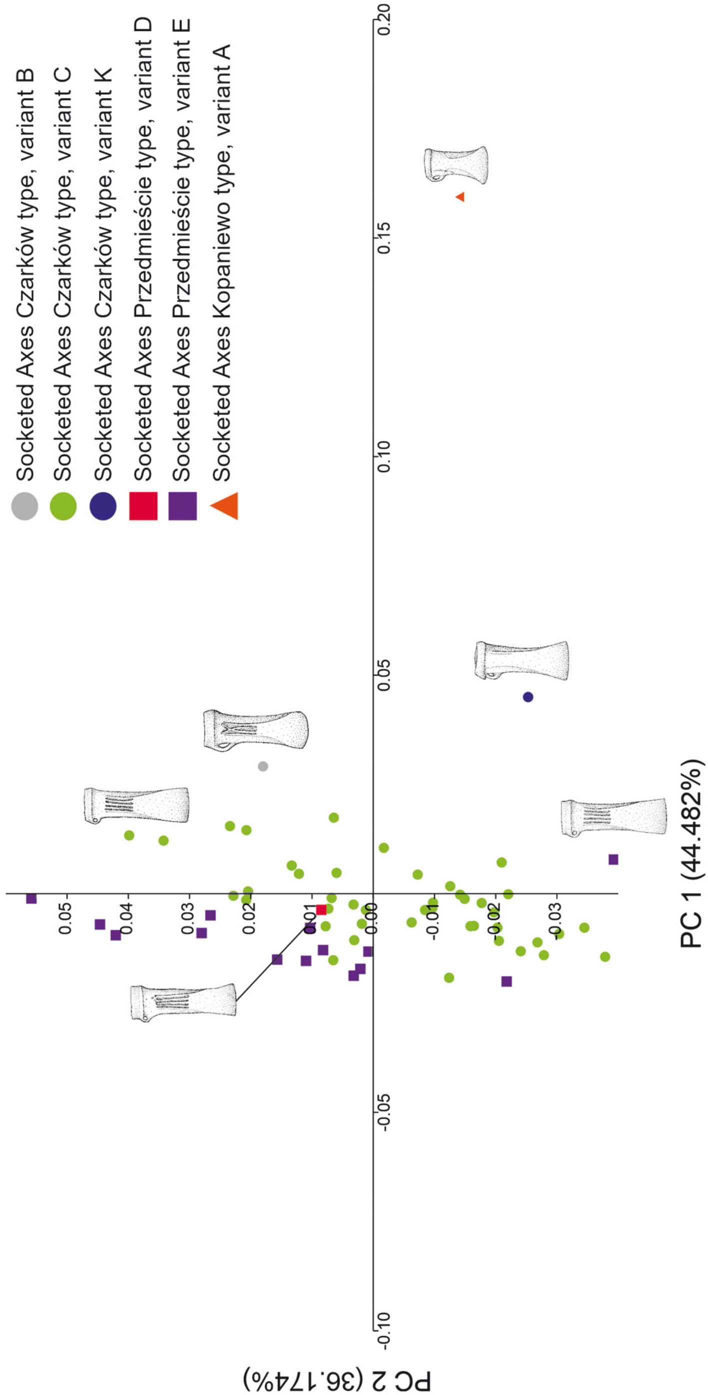

Fig. 6. Scatter plot of the first two principal components (PC1 and PC2) obtained using the landmark method

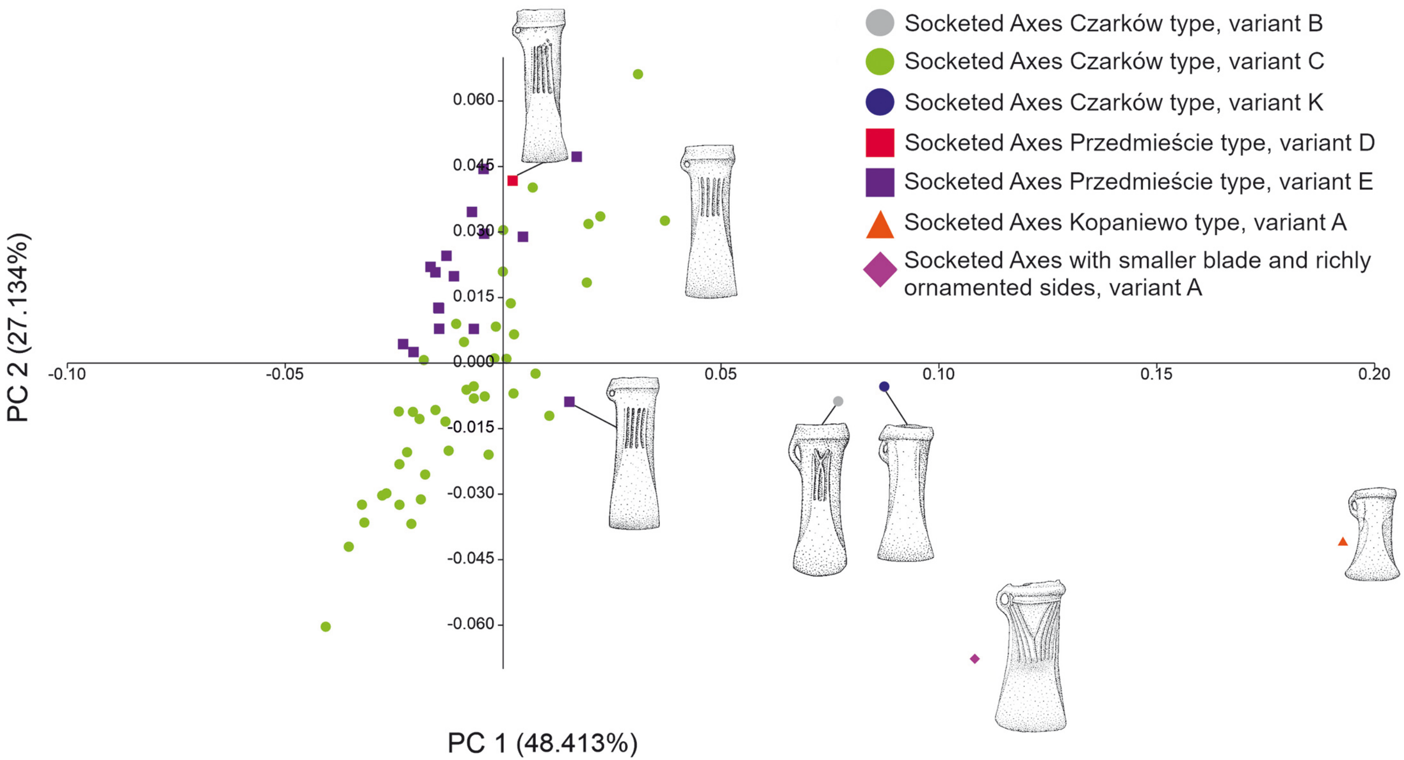

Fig. 7. Scatter plot showing the first two principal components (PC1 and PC2) derived from the outline method

Table 6. Percentage distribution of variance for the first 10 components from the entire dataset for the landmark method

PC	Eigenvalue	% of variance	% of cumulative variance
1	0.00130953	48.413	48.413
2	0.000733959	27.134	75.55
3	0.000289184	10.691	86.24
4	0.000127982	4.7314	90.97
5	4.59341E-05	1.6982	92.67
6	4.28205E-05	1.5831	94.25
7	3.42749E-05	1.2671	95.52
8	2.50288E-05	0.92531	96.44
9	1.79219E-05	0.66257	97.11
10	1.38117E-05	0.51061	97.62

Table 7. Percentage distribution of variance for the first 10 components from the entire dataset for the outline method

PC	Eigenvalue	% of variance	% of cumulative variance
1	0.000565763	44.482	44.482
2	0.000460091	36.174	80.656
3	8.14316E-05	6.4024	87.0584
4	4.45769E-05	3.5048	90.5632
5	3.22546E-05	2.5359	93.0991
6	1.87498E-05	1.4742	94.5733
7	1.0624E-05	0.83529	95.40859
8	8.81168E-06	0.6928	96.10139
9	7.69188E-06	0.60476	96.70615
10	7.41535E-06	0.58301	97.28916

outline method-based PCA revealed that particular axes exhibited significantly different shapes compared to other specimens (Fig. 7). As in the case of the landmark method, these are the following axes: the Kopaniewo type, variant A, with a strongly reduced cutting edge and richly decorated sides, variant A, and the Czarków type, variant K. The Czarków type, variant C and the Przedmieście type, variant E, share comparable features, though some differences are evident. Minor variations occur in the shape of the cutting edge, while more pronounced differences are observed in the loop area. For the Czarków type axes, the loop is slightly higher, and the transition from the loop to the socket mouth is smoother. Analysis of data concentration based on the first two PCs for the outline method shows the following patterns: axes of the Kopaniewo type, variant A and the Czarków type, variant K, are scattered apart from other specimens along the positive values of the PC1 axis. The Czarków type, variant C axes are primarily distributed along the PC2 axis, particularly at the negative values of PC1. Bronzes of the Przedmieście type, variant E, are positioned along the positive values of PC2. Notably, the axes of the Kopaniewo type, variant A, and Czarków type, variant K, appear in the lower part of the graph, along the positive values of PC1, and are positioned away from other axes. The Czarków type, variant B, is located in the upper part of the graph. The Przedmieście type axe is centrally positioned above the PC2 axis, amidst the axes of the Czarków type, variant C and Przedmieście type, variant E.

DISCUSSION

The results of the GMM analyses of the Rosko axes allowed us to answer the research questions posed at the beginning of the article.

The answer to the question regarding morphological differences in the characteristic points of the studied objects is twofold. The first part pertains to the following axes: Czarków type, variants B and K, Kopaniewo type, variant A, and the axe with a strongly reduced cutting edge and richly decorated sides, variant A. These specimens are represented by individual objects that stand out from the rest of the deposit. They feature wider cutting edges and socketed mouths. The point distribution on scatter diagrams from both the landmark (Fig. 6) and outline (Fig. 7) methods confirms their distinctly different shapes compared to the other artefacts. Notably, the Czarków type, variants B and K, despite belonging to the same type, do not resemble the Czarków type, variant C. The differences are evident in their socket decorations, which vary between variants, as well as in the distinct shapes of their loops and socket mouths. The second part of the answer concerns the differentiation among the remaining axes: Czarków type, variant C and Przedmieście type, variants E and D. The first two groups differ in several aspects. Apart from the previously mentioned socket ornamentation and collar height, the Czarków type, variant C axes have a visibly wider cutting edge and slightly greater width at the narrowest point. In contrast, the Przedmieście type, variant D axe closely resembles the Przedmieście type, variant E axes, differing mainly in ornamentation, which justifies their classification within the same type. Graphs generated after Procrustes transformation for both the landmark method (Fig. 4) and the outline method (Fig. 5) illustrate that the Przedmieście type, variant E and the Czarków type, variant C axes show variability within their respective types, with individual specimens differing significantly. This explains the scattered distribution of points in the scatter diagrams for both the landmark and outline methods. Notably, the Czarków type, variant C axes exhibit greater variation compared to the other groups.

The analysis of the axes concerning their potential production from the same casting mould should primarily focus on the Przedmieście type axes, variant E, and the Czarków type axes, variant C, as multiple specimens represent these groups. Two key features to consider are their external shapes and the ribs on the sockets, which vary between variants. The PCA scatter plots indicate that no points overlay altogether; some overlay only partially, making it impossible to conclusively determine whether the axes were produced in a single casting mould. Discrepancies are also evident in the absolute measurements of individual variants. These variations could have been influenced by post-casting modifications, such as the removal of sprues or seams, as well as the use of the axes. Analysis of the two most numerous axe groups revealed a high standard deviation for the measurements of the Czarków type, variant C, and a lower standard deviation for the Przedmieście type, variant E (Table 2), indicating greater dispersion of results around the mean for the former. Similar patterns were observed for width and length indices, with the Czarków type, variant C, showing higher standard deviation values compared to the Przedmieście type, variant E. PCA results confirm these differences between the two groups in both absolute measurements and indices, which explains the scatter of axes in the diagrams. An interesting feature highlighted in the PCA landmark analysis (Fig. 4) is the variation in flange height. As with other landmarks, this variation is reflected in the greater scatter of data points for the Czarków type axes, variant C.

The landmark and outline diagrams indicate that the shape of the cutting edge is characteristic of specific variants and is consistent for most of the Czarków type, variant C, and Przedmieście type, variant E axes (Figs 4 and 5). While some axes show damage to their cutting edges, this damage was probably not caused by use. The absence of significant similarities between the artefacts from both the Czarków type, variant C and the Przedmieście type, variant E, indicates that the axes from these groups were cast from more than one mould. Differences in their shapes were likely influenced primarily by post-production processes, such as the removal of casting overflows and casting jets, or the cold hammering of the cutting edges (*cf.*, Nowak 2018, 120). Notably, Przedmieście type axes were produced locally. In contrast, the Czarków type is characteristic of finds from Lower Silesia, indicating that communities from these two regions maintained contacts and suggesting that populations from the vicinity of modern Rosko were also part of this network (Machajewski and Maciejewski 2006, 144). This connection, however, is unsurprising given the intensity of interactions between Silesia and Greater Poland documented in various categories of archaeological sources (Kaczmarek 2012). Despite the observed overlap between the Czarków type, variant C, and the Przedmieście type, variant E series, it is essential to note that the 2D GMM analysis did not account for variations in socket ornamentation. This factor can significantly influence the typological classification of these artefacts.

The diagrams show (Figs 4, 5) that the shapes of the Przedmieście type axes, variant E, and the Czarków type, variant C – in addition to those noted by Kuśnierz (1998, 33-53) – also differ in the width of their cutting edge, which is narrower for the Przedmieście type, variant E axes. Additionally, the transition from the loop to the socket mouth is distinct between the two types. This section is straight for the Czarków type, variant C, whereas the Przedmieście type exhibits a gentler, curved shape. The internal variation within these types presents challenges. Landmark method analysis of the Przedmieście type axes (Fig. 4) indicates greater homogeneity within this group, as the points on the diagrams are closely clustered. In contrast, the Czarków type, variant C, demonstrates more variation in the assigned landmark points. Outline method analysis of the overall shapes (Fig. 5) indicates that some axes feature a lower loop position and a differently shaped sleeve orifice. The greater variation in the Czarków type, variant C, is confirmed by the high standard deviation values for absolute measurements, as well as width and length indices (Tables 2 and 3). By comparison, these values are generally lower for the Przedmieście type, variant E. The issue of internal variation, particularly for the Czarków type, variant C, requires further investigation. A study involving a larger sample of artefacts from other sites of this period would be essential to resolve these questions.

The obtained results were made comparable by applying both the landmark and outline methods. Using the landmark method, 13 specifically located points were identified (Fig. 3), enabling a direct analysis of the characteristic features of the investigated objects. In contrast, the outline method allowed for the examination of individual artefacts as a whole set, facilitating the observation of overall shape similarities (Fig. 5).

The analysis yielded a different number of principal components, reflecting the morphological variation of the axes. PCA scatter plots confirm the distinctly different shapes of the Kopaniewo type, variant A axes, an axe with a strongly reduced blade and richly decorated sides, variant A, and the Czarków type, variants B and K. The differences between these and the other objects were also evident in absolute measurements (Machajewski and Maciejewski 2006). These specimens consistently appear apart from the clusters representing the more numerous artefacts. The Czarków type, variant C and Przedmieście type, variant E axes do not form specific, compact clusters in the diagrams, which may indicate internal variation within these variants. This variability complicates their assignment to particular types and variants, suggesting the influence of both technological processes and subsequent use. Some points on the scatter diagrams are very close to each other or partially overlap, indicating a high degree of similarity in certain features.

It should also be noted that post-production processes, such as the removal of casting seams shortly after moulding, may already introduce shape modifications perceptible to the highly sensitive GMM method. Furthermore, prolonged use, resharpening, or damage repair may lead to additional morphological alterations that accumulate over time. In the case of artefacts from Rosko, analyses of traces of production and use were also carried out. We plan to devote further publications to the integration of this data. In future studies based on substantially larger samples, these factors may prove to have a more pronounced impact, helping to disentangle production-related variation from use-related transformation. Such research is essential to refine our understanding of formal variability among socketed axes and to contextualise GMM results within the full life cycle of these tools.

The method chosen for conducting a 2D GMM analysis should be determined by the state of preservation of the investigated objects (Wilczek 2017, 24) and the study's objectives. In this case, the application of the landmark and outline methods enabled a 2D morphological analysis of the axes as complete artefacts, as well as a focused study of the points defining the height of the collar. A notable limitation of the 2D GMM approach was the exclusion of certain parts of the axes that could have distorted the final results. This issue affected only three artefacts in this study. Future research is planned using 3D scans and traceological analyses.

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References

Adams D. C., Rohlf F. J. and Slice D. E. 2004. Geometric morphometrics: Ten years of progress following the 'revolution'. *Italian Journal of Zoology* 71/1, 5-16.

Bookstein F. L. 1997. Landmark methods for forms without landmarks: Morphometrics of group differences in outline shape. *Medical Image Analysis* 1/3, 225-243.

Brandt S., Sole C., Lyle R. and Pirk C. 2023. Geometric Morphometric Analysis of Ocular Patterns as a Species Identifier in the South African Endemic Trapdoor Spider Genus Stasimopus Simon, 1892 (Araneae, Mygalomorphae, Stasimopidae). *Evolutionary Biology* 50/3, 350-364.

Cardillo M. 2010. Some applications of geometric morphometrics to archaeology. In A. M. T. Elewa (ed.), Lecture Notes in Earth Sciences. *Morphometrics for Nonmorphometricians* (= LNEARTH 24). Berlin, Heidelberg: Springer, 325-341.

Cooke S. B. and Terhune C. E. 2015 Form, Function, and Geometric Morphometrics. *The Anatomical Record* 298, 5-28.

Dąbrowski J. 1968. *Zabytki metalowe epoki brązu między dolną Wisłą a Niemnem*. Wrocław: Zakład Narodowy im. Ossolińskich.

Hammer Ř., Harper D. A. T. and Ryan P. D. 2001. PAST: Paleontological Statistics [Software].

Kaczmarek M. 2002. *Zachodniowielkopolskie społeczności kultury łużyckiej w epoce brązu* (= *Seria Archeologia* 48). Poznań: Wydawnictwo Naukowe Uniwersytetu Adama Mickiewicza.

Kaczmarek M. 2012. *Epoka brązu na Nizinie Wielkopolsko-Kujawskiej w świetle interregionalnych kontaktów wymiennych* (= *Prace Komisji Archeologicznej – Poznańskie Towarzystwo Przyjaciół Nauk* 28). Poznań: Wydawnictwo PTPN.

Kuśnierz J. 1998. *Die Beile in Polen III: (Tüllenbeile)* (= *Prähistorische Bronzefunde* 9/21). Stuttgart: Franz Steiner Verlag.

Machajewski H. and Maciejewski M. 2006. Skarb ludności kultury łużyckiej z Roska nad Notecią. In H. Machajewski and J. Rola (eds), *Pradolina Noteci na tle pradziejowych i wczesnośredniowiecznych szlaków handlowych*. Poznań: SNAP Oddział w Poznaniu, 127-146.

Masojć M., Gismallah A. H., Michalec G., Gałaś A., and Jórdeczka M. 2020. Acheulean Bifaces from Khor Shambat, Omdurman (Sudan). Comparative Studies in the Nubian Context. *Archaeologia Polona* 58, 39-62.

Mayer E. F. 1977. *Die Äxte und Beile* in Österreich (= *Prähistorische Bronzefunde* 9/9). München: C.H. Beck.

Nowak K. 2018. Badania nad rekonstrukcją sposobów wytwarzania wybranych typów narzędzi metalowych w późnej epoce brązu. Dwuczęściowe gliniane formy odlewnicze. *Śląskie Sprawozdania Archeologiczne* 60/2, 97-124.

Novotná M. 1970. *Die Äxte und Beile in der Slowakei* (= *Prähistorische Bronzefunde* 9/3). München: C.H. Beck.

Rohlf F. J. and Marcus L. F. 1993 A revolution of morphometrics. *Trends in Ecology & Evolution* 8/4, 129-132.

Rohlf F. J. 2021. tpsDig2 (Version 2.32) [Software]. Anthropology and Ecology & Evolution Stony Brook University.

Rohlf F. J. 2022. tps Util (Version 1.82) [Software]. Anthropology and Ecology & Evolution Stony Brook University.

Serwatka K. 2020. Analiza geometryczno-morfometryczna sierpów z krzemienia ożarowskiego. In W. Brzeziński (ed.), *Kopalnie krzemienia na stanowisku 'Za garncarzami' w Ożarowie*. Warszawa: Państwowe Muzeum Archeologiczne, 223-228.

Slice D. E. (ed.) 2005. *Modern morphometrics in physical anthropology*. Boston: Kluwer Academic/Plenum Publishers.

Wilczek J. 2017. *New approaches for the acquisition, systematisation and interpretation of archaeological artefacts*. Doctoral thesis Brno: Masarykova univerzita, Filozofická fakulta – manuscript available online: https://theses.cz/id/2507sl/ accessed 28.12.2023.

Wiśniewski A., Serwatka K. and Badura J. 2015. Nowe znaleziska kultury prądnickiej z terenu Płaskowyżu Głubczyckiego. *Śląskie Sprawozdania Archeologiczne* 57, 7-30.