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Breaking sickles for shaping money. Testing the accuracy of weight-based fragmentation

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ABSTRACT

Bronze is considered a key commodity during the European Bronze Age (BA, 2200-800BC). Recent studies have shown that, mostly during the Late Bronze Age (Late BA, 1300–800 BC), fragmented bronze objects were subjected to regulation consistent with a Pan-European weight system. This hypothesis is mostly based on statistical analyses of weights. In this article, we present the results of an experiment in which sickle replicas were broken up and the resulting fragments weighed and compared with examples attested from the BA. The purpose of the fragmentation was to obtain pieces complying with certain weight patterns similar to regularities observed in archaeological fragmented sickles and fragmented objects in general. Results of the fragmentation experiment have been compared with a statistical analysis of c. 1500 fragmented sickles from European BA hoards, concluding that archaeological and replica fragments share the same metrological characteristics. We suggest that rough weight-regulated fragmentation is possible even by persons with no metallurgical skill, and that both inaccurate and 'unwanted' fragments probably comprise the known archaeological examples. The article demonstrates that statistical analyses usually employed in similar research allow for detecting the existence of weight systems even in a dataset characterized by the significant presence of random values.

1. Introduction

The presence of large amounts of fragmented metal objects in Late BA contexts is a well-established fact in European archaeological studies of the period (e.g., Rezi, 2011; Wiseman, 2018; Lago, 2020). Some authors have interpreted the occurrence of fragmentation as ritualistic with a votive purpose (e.g., Nebelsick, 2000; Hansen, 2016), while others have explained it as connected to metal recycling habits (e.g., Wiseman, 2018). Several authors have also suggested that fragmented bronze objects had an economic meaning/purpose, with potential use as a means of exchange (e.g., Peroni, 1966; 2004; De Rossi, 1986; Sommerfeld, 1994; Primas, 1997). Recent studies have shown that bronze fragments from Italian and Central European BA hoards were weight regulated, and in compliance with the same weight system used for balance weights. This might suggest the existence of a monetary system involving fragments of metal objects and weighing equipment. Following this hypothesis, at least a statistically significant number of bronze fragments must have been fragmented on purpose in order to obtain pieces with a specific weight (Ialongo and Lago, 2021). It remains unclear whether the weight-based fragmentation necessarily required the intervention of metalworkers or, instead, bronze fragmentation could be part of price negotiation within the trade, i.e. potentially achievable by any economic agents negotiating the price of a particular commodity. Furthermore, the hypothesis that what we observe through statistical analyses of weighed fragments is compliant with weight-based fragmentation processes needs further investigation.

This paper presents the results of an archaeological experiment conducted by breaking up bronze sickle replicas to obtain fragments complying with a pre-established metrological system. The fragments obtained during the experiment have been statistically analyzed,

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comparing the results with c. 1500 fragmented sickles from European Late BA hoards[1]. This research provides new information about intentional and supervised fragmentation as well as the use of statistics in understanding the character of weight systems in prehistoric Europe.

1.1. Metrology and money in the European bronze age

The adoption of weighing technology represented a milestone in the economy of the European BA, leading to change the ways in which metal-based money was conceived and circulated. From the Early BA (2200–1550 BCE) in Central Europe – before the first evidence of balance beams and balance weights – there are well-attested money-objects made of fahlerz copper without nickel (Junk et al., 2001), shaped like open rings with curled ends (*Ösenhalsringe*), ribs (*Spangenbarren*), and possibly flanged axes. They are complete, unused, and apparently standardized in shape and dimension (Lenerz-de Wilde, 1995; 2002). The likeness between the objects and their relative fungibility allowed them to be used as a medium of exchange, although they were not precisely weighed and did not follow any strict metrological system (Pare, 2013: 513; Kuijpers and Popa, 2021). The first attested weighing tools (beams and balance weights) in continental Europe date no earlier than the Middle -Late BA (1550–800 BCE), and the identification of European BA weighing equipment and systems is relatively recent (Medović, 1995; Cardarelli et al., 1997; 2001; 2004; Pare, 1999; Peroni, 2001; Roscio et al., 2011). Following the ERC funded project entitled 'Weight and Value' (Ialongo, 2019; Ialongo and Rahmstorf, 2019), available data have increased considerably.

The study of ancient weight systems is based on the identification of a precise order of weight multiples in a given data distribution, where the most commonly used method is Frequency Distribution Analysis (FDA) (Cardarelli et al., 1997; 2001; 2004). The FDA allows for the observation of data distributions and the identification of potential clusters of values. The presence and position of distinct clusters, highlighted by peaks, can indicate that they are multiples of each other (see § 2.3.1). In some studies, the method is integrated with the Cosine Quantogram Analysis (CQA) (see § 2.3.2), a statistical approach allowing for the identification of a base unit in a numerical dataset. This is often applied in combination with a significance test (e.g.the Monte Carlo test) assessing the validity and non-randomness of the result (see § 2.3.2) (e.g. Ialongo and Rahmstorf, 2019; Ialongo and Lago, 2021). The described methodology has led to the identification of two orders of magnitude in balance weights. Piriform and lenticular (*Kannelürensteine*) weights are generally heavier, having a weight unit of c. 420–450 g (Rahmstorf and Ialongo, 2020; Ialongo and Rahmstorf, 2022), mainly concentrated within the *mina* range. Disc, rectangular and spherical weights fall into the *shekel* range, whose weight unit is 9.4–10.2 g (Ialongo and Rahmstorf, 2019). Recent research on this topic has shown that this is a Pan-European weight unit (Ialongo et al., 2021), which partly confirms the presence of a Central European metrological system suggested by previous research (Pare, 2013: Table 29.2). The introduction of weight technology is approximately contemporary with the phenomenon of the fragmentation of bronze objects (Lago, 2020), which became the main metal-based money until the end of BA. In this context, the examined fragmented bronze objects fall into the *shekel* range. By analyzing them with the same methods used for the study of balance weights, they appear to share the same metrological characteristics (Ialongo and Lago, 2021).

The idea that bronze fragments could be used as money has been discussed for well over a century in European BA studies, particularly among Italian and German scholars (De Rossi 1886; Peroni 1966; 1998; Primas 1986; Sommerfeld 1994). The most important and influential research on this topic has long been *Gerätegeld Sichel* by Chr. Sommerfeld (1994). Sommerfeld collected weight data of complete and fragmentary objects from central-northern German and western Polish hoards containing sickles. The weight of objects from larger hoards was analyzed using FDA, showing cases of data clustering around multiples of 5 or 10 g (e.g. artifacts from Weißig, Straupitz, Ruthen: see Sommerfeld 1994: 39-40). However, this and other research employing the same methodology (Primas, 1986; Peroni, 1998) have been considered unconvincing (Pare, 1999; 2013: 516). The lack of firm ground of metrological analyses on bronze fragments was partly due to still limited knowledge of weight systems until a few years ago, while a system based on weighted fragments as currency was hardly conceivable without well-established standard weights (Pare, 2013: 517). The current state of research has allowed for a comparison of standard weights based on European balance weights to a large sample of fragmented objects from Late BA Italian and German hoards on the basis of the FDA, CQA and the Monte Carlo test. The FDA of bronze fragments showed weight peaks approximately every 10 g (10, 20, 30, 40, 50 etc.), while CQA indicated a weight unit of 9.8 g., i.e. substantially the same as balance weights (Ialongo and Lago, 2021: Fig. 5).

1.2. Analyzing European BA bronze sickles

As part of the PhD research of one of the authors (GL) at the Sapienza University of Rome, a large amount of weight data of published objects from European BA hoards has been collected (Lago 2020-2021). This database has been used for this research by filtering all the fragmented sickles, constituting c. 1500 weighed LBA pieces from Central Europe (Germany, Poland, Austria, Slovenia, Switzerland) and Italy (Fig. 1). This archaeological sample has been analyzed in order to determine whether a metrological system can be identified and the results of the analysis act as a benchmark for experimental fragments. The FDA of fragmented sickles is multimodal, showing peaks of value almost regularly focused around multiples of the Pan-European weight system (9.4–10.2 g) (Fig. 11, a). The CQA applied to a range from 7 to 200 g

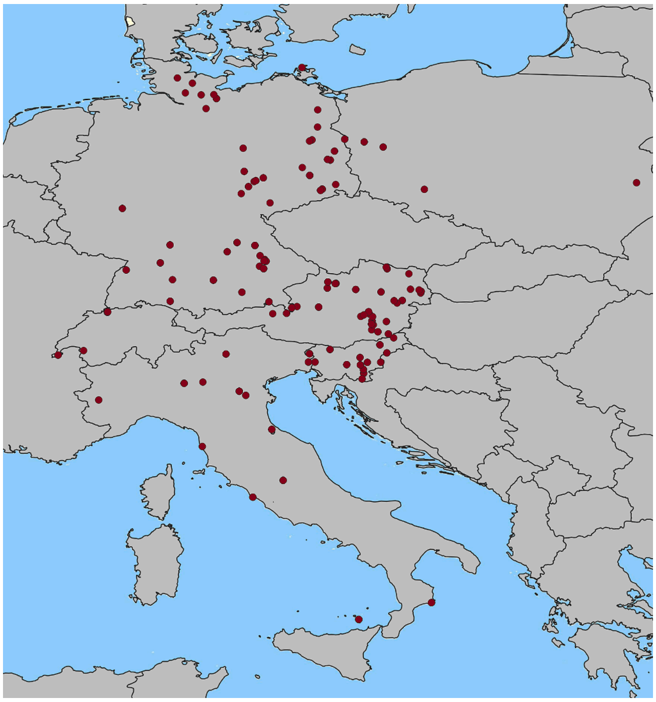

Fig. 1. Distribution of fragmented and weighed sickles from European BA hoards.

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[1] In this article, we discuss the metrological analyses only focused on sickle fragments from hoards. The hoards gave us the opportunity to analyze through statistical means a large quantity of objects collected and published together. However, we are not suggesting that money fragments and monetary fragmentation is confined to these kinds of contexts or objects.

(1422/1533 fragments) also yielded positive results, showing highest peaks at c. 9.8–10 g, while Monte Carlo tests showed the CQA result to be statistically significant and being the best quantum above the 5% alpha significance threshold. Therefore, the results confirming 9.8–10 g as the most probable basic unit (Fig. 11, c). The fragmentation experiment presented in this paper is based on these results, aiming to replicate the archaeological evidence. The goal of the experiment was trying to obtain sickle fragments with weights that are multiples of 10 g (set as weight unit), with 10, 20, 40, and 80 g units arbitrarily chosen as target values.

1.3. *Experimental archaeology of bronze fragmentation*

Experiments in archaeology have become an essential means for testing hypotheses by replicating objects and processes to create reference collections to validate or disprove the initial hypotheses. In recent years, some experiments have investigated the possible use of bronze items – especially weapons – by comparing use wear traces produced during the experiments with those observed on archaeological specimens (e.g. Dolfini and Crellin, 2016; Gentile and Van Gijn, 2019; Hermann et al., 2022). Comparable research for deliberately fragmented objects is scarce. In this respect, the most important studies on experimental bronze fragmentation have been recently conducted by M. G. Knight, whose research on Late BA socketed axes (Knight, 2017), and spearheads and swords (Knight, 2019) are the only possible comparison with the research presented here. The experiments aimed to test which instruments – hammers or chisels - are more effective at breaking up heated bronze objects and to what extent temperature and their composition influences the breaking process. A first reference collection of breaking marks that might be compared with archaeological specimens was been created. The most relevant results show that archaeologically attested fragmented bronze objects were probably pre-heated, and such objects do not necessarily preserve traces of how they were broken (Knight, 2019: 14). The deliberate fragmentation of a bronze fragment has been proven to be a simple procedure once the metal is properly heated. For the experiment presented here, we benefited from these observations, and focused on breaking up only pre-heated objects, and using some of the breaking methods already tested in previous studies (hammering and chiseling), along with new ones (direct striking with a bronze axe). To date, no other fragmentation experiments on bronze sickles have been published. Furthermore, because of the specificity of our research question, the pursued protocol is independently and originally conceptualized, not relying on similar previous studies.

2. Materials and methods

The experiment was conducted in the Terramara di Montale archaeological park and open-air museum of the Terramara of Montale (Modena, Italy) in June 2021. It consisted of two preparatory stages: the production of bronze sickles and an equal arm balance replica, followed by two experimental stages: sickle fragmentation and weighing of the fragments. Finally, the fragments were weighed with a modern digital scale in order to statistically analyze the experimental results (the experimental form is published as supplementary material).

2.1. *Materials*

2.1.1. *Sickle production*

We produced two types of bronze sickles: tanged and knobbed. The selection of models was arbitrary, choosing among all the types of which at least one intact specimen is preserved. The model used for tanged sickle replicas (*Zungensicheln*, hereafter ZS) was the Corcelettes type, no. 1357, while for the knobbed sickles (*Knopfsicheln*, hereafter KS) we replicated a type Penkhof II (variante C), n. 180 (from the typology of Primas, 1986). Unfortunately, compositional data of these specimens are not provided by author. Since the chemical composition, and in particular the percentage of tin, is a variable to be considered, we choose to make two different alloys: a low-tin copper alloy (c. 4% Sn) and a high-tin copper alloy (c. 10% Sn). These were based on archaeological evidence (low-tin copper alloy sickles from Slovenia: Teržan, 1995; and Poland: Nowak et al., 2019. High-tin copper alloy sickle from Switzerland: Rychner, 1981: 111; Rychner and Stós-Gale, 1998: 172–173). We produced 20 bronze sickles (10 ZSs and 10 KSs), making alloys with 99.95% pure copper (Cu) ingots and tin-based wires (Sn97Cu3). The ratio of copper to tin was calculated in advance, weighing the metals before starting the melting (Table 1). Three of the 20 replicas were miscast, but were nevertheless used for the experiment. Production of sickles was performed by using sand molds, a technique not attested in archaeological record but probably already used during the European BA (Ottaway and Seibel, 1997; Wang and Ottaway, 2004: 9). This phase of the experiment was conducted by the authors skilled in metalworking (FS, LP, ALT).

The procedure for preparing the bronze casting was as follows:

1. Preparation of accurate wooden replicas of sickles (Fig. 2 a).
2. Assembling of the sand mold. It was made of two wooden pallets filled with wet sand. In order to have the right consistency and compactness to hold the casting, the sand mold was gradually hydrated till it reached the correct consistency. Both surfaces of the mold were hammered to impress the shape of the wooden sickle placed between them. The model was subsequently removed, leaving the cavity for the cast. Finally, the pallets were tied as firmly as possible with leather straps, preserving the cone through which the molten metal would be poured (Fig. 2 b-c).
3. Preparation of the casting pit. After lighting the fire, it was stoked with charcoal and air was constantly blown by leather bellows through tuyeres to reach and hold a the temperature of over 1300C° in the furnace for a few minutes (Fig. 2 d-g).
4. A ceramic crucible was placed in the casting pit under the burning coals and positioned to face the incoming air blown through the tuyeres. The copper was placed into the pit and, after it melted, the tin wires were added. The molten metals within the crucible were continuously stirred with a wooden stick to ensure full liquefaction and mixture of the alloy. Next, the crucible was removed from the furnace and its contents were poured into the vertically oriented mold, filling the cavity and avoiding pieces of coil from entering into it. After a few seconds, the bronze sickle was removed from the mold and cooled either by air or water (Fig. 2 h-i).

ZS replicas were produced by leaving the casting cone in the upper central part of the blade, while the KS replicas had it at the base. The cone position is based on several stone mold specimens discovered in Central Europe (e.g. tangled: Primas, 1986: nos. 803, 804, 1034, 1036, 1197; knobbed: Sommerfeld, 1994: Pl. 58, 16; Furmánek and Novotná, 2006: nos. 285, 290).

Given the non-functional purpose of the production, the KS replicas were made without the characteristic knob – which would have required more time – and all the newly forged objects were left with their casting burrs and cones, making the weight of complete objects higher than the archaeological specimens (Fig. 2; Table 1).

2.1.2. *Balance scale replica production*

The experiment was conducted by using five equal arms balance scales: three were made of animal bones and two of wood. Two bone balance scales had been previously made for an already published experiment (named B 4 and B 5 in this research, they are respectively B04 and B08 in Hermann et al., 2020a) and very kindly lent for the present study. The other three balance scales were made by one of the authors (MC) using industrial equipment with the sole purpose of obtaining a faithful replica of the originals. The bone balance scale (B 1) uses a cattle femur (*Bos taurus* L.), based on the Bordjoš balance (Medović, 1995: Abb. 4). The wooden balance scale (B 2, B 3) were

Table 1
Dimensions and alloy of the replica sickles.

ID	model	Sn %	Cu (g)	Sn (g)	cooling method	final weight (g)	waste bronze (g)	lenght (cm)	base width (cm)	mid-blade width (cm)	mid-blade thickness (cm)	end blade thickness (cm)	rib max thickness (cm)	note
Z_01	ZS	4	192	8	open air	122	70				0.34	0.29	0.45	miscast
Z_02	ZS	10	180	20	open air	159	23	12.63	2.15	3.92	0.37	0.28	0.42	
Z_03	ZS	4	192	8	open air	179	21	12.65	2	4.21	0.35	0.27	0.51	
Z_04	ZS	4	192	8	water	155	9	12.75	2	4.04	0.35	0.29	0.47	
Z_05	ZS	10	180	20	water	178	6	12.75	2.06	4.28	0.35	0.27	0.47	
Z_06	ZS	10	180	20	water	148	17	12.77	2.05	4.02	0.38	0.25	0.47	
Z_07	ZS	4	192	8	water	109	24	12.64	2.03			0.27		miscast
Z_08	ZS	10	180	20	water	179	3	12.75	2.04	4.05	0.31	0.25	0.54	
Z_09	ZS	4	192	8	water	156	23	12.89	2.01	4.12	0.35	0.2	0.48	
Z_10	ZS	10	180	20	water	138	58	12.76	2.06		0.39	0.28	0.48	
K_01	KS	10	270	30	open air	270		17.3	3.39	3.2	0.44	0.32	0.72	
K_02	KS	4	288	12	open air	245	22	17.4	3.32	3.37	0.49	0.26	0.8	
K_03	KS	4	288	12	open air	189	94	15.6	3.24	3.1	0.41	0.33	0.76	
K_04	KS	10	270	30	water	203	87		3.35		0.46	0.32	0.69	miscast
K_05	KS	4	288	12	water	162	69	16.9	3.07	2.92	0.41	0.28	0.68	
K_06	KS	10	270	30	water	252	33	17.4	3.26	3.12	0.43	0.31	0.67	
K_07	KS	4	288	12	water	190	66	15.4	3.2	3.05	0.48	0.37	0.76	
K_08	KS	10	270	30	water	278	12	17.3	3.08	3.42	0.78	0.35	0.8	
K_09	KS	10	270	30	water	213		17.4	3.3	3.16	0.42	0.32	0.67	
K_10	KS	4	288	12	water	238	43	16.3	3.18	3.33	0.42	0.26	0.67	

Fig. 2. Examples of sickle replicas. a. sickle replicas in wood; b-c. production and use of the sand mould. d-e; preparation of the casting pit feeding the coals with air blown by tuyeres; f-g. melting of copper and tin inside a crucible; h. pouring the obtained bronze alloy into the sand mould; i. removing the replica from the mould.

inspired by a bone specimen from the Migennes inhumation burial no. 298 (Roscio et al., 2011: Figs. 5, 13): their assembly was very quick and easy, requiring only basic equipment. The very low number of archaeological sites where balance scales have been found – despite a conspicuous number of balance weights – suggests that many were made of a perishable material such as wood (Ialongo, 2019: 7; Poigt et al., 2021: 9) (Fig. 3). All the balance scales were equipped with rounded leather pans, tied with cotton or hemp wires. Little portions were carefully removed either from the pans or the wires in excess, whenever it was necessary to balance the beam with pans charged with the same – or no – weight.

2.1.3. *Balance weight selection*

We collected a few sea pebbles to be used as balance weights that had the following values: 10, 20, 40, 80 g (see § 1.1.). As mentioned above, the balance weights relate to a system where the basic unit is 10 g and

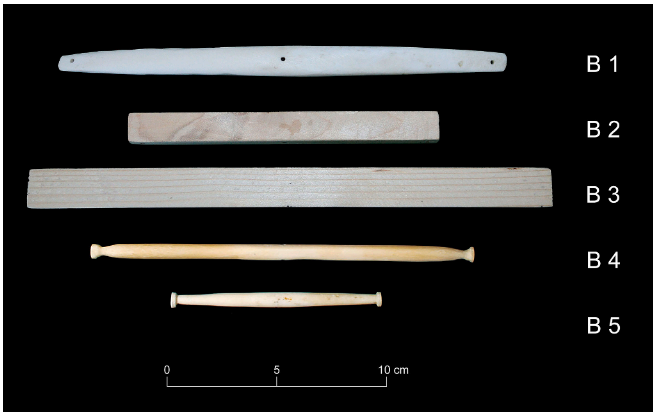

Fig. 3. Equal arms balance scales. B4 and B5 after Hermann et al., 2020.

some multiples of this value. The basic unit '10' was chosen because it is very similar to the European BA one in range value of a *shekel* (Ialongo et al., 2021). The actual weights of the selected pebbles (measured with a digital scale) are: 10.1, 10.11, 10.15, 19.99, 20.08, 20.18, 20.21, 39.4, 40.14, 40.17, 80.11 g.

2.1.4. *Tools*

Three hammers, one axe and three chisels were used to break up the replicas. These tools were already in possession of experimenters. The axe (A 1) was hafted with a wooden handle, and the blade fixed with wet leather straps. It was made of a copper-based alloy with 12% tin content. The wooden hammer (H 1) was carved from boxwood, while the stone hammers (H 2, H 3) contain pebbles randomly collected from a riverbank. The chisels (CH 1, CH 2, CH 3), reproducing Italian BA types, were made with the same alloy as the bronze axe (Fig. 4).

2.2. *Methods: The fragmentation and weighing experiment*

All the breakings up of the replica sickles sought to produce fragments with a predetermined weight target. The entire fragmentation experiment is based on trying to get fragments of predetermined weight to compare with archaeological data, and no attention was paid to replicating the shape and/or dimensions of the archaeological sickle fragments.

2.2.1. *Sickle fragmentation*

Considering that the breaking of an unheated object is very difficult and proved to be ineffective in other experiments (e.g. Knight, 2018), we only tested methods involving object heating. This phase of the experiment was conducted by the authors with no metalworking skills (GL, MC). Eighteen sickles were heated in a casting pit by increasing the temperature - detected by using a thermocouple (type K) - from ~ 600 to ~ 1140C°. Two sickles were heated by placing them in a campfire, where the thermocouple registered a temperature range between ~ 400 and ~ 900C°. The preparation procedure is the same for all the tested methods: 1. The temperature was kept high (on average ~ 1000C° in the casting pit and ~ 800C° in the campfire) by blowing air through the tuyeres. 2. The sickle was placed under the burning coals with air being blown in. 3. The sickle was removed when it turned red and was then either held with pliers or placed on a hard surface, depending on the fragmentation technique that would be performed. The sickle was hit while hot enough to enable fragmentation, afterwards was heated again to renew the experiment.

Three methods of fragmentation on the heated sickles were tested by conducting 23 experiments on 20 sickles: 1. Placing the sickle on a hard surface and hammering the non-leaning portion; 2. Hitting the sickle with a bronze axe; 3. Chiseling the sickle. Our skills progressively improved during the experiment, helping us to better evaluate the size of the fragments and allowing for a more conscious premeditation of the breakage (Fig. 5).

2.2.2. *Hammering*

A wooden hammer (H 1) was used for direct percussion in all the hammering experiments. The sickle was held with the pliers: the portion to be broken off was first leant over the edge of a support and then hammered. The technique was successfully performed on sickles with both low and high tin content. As already observed in other experiments, breaking was easier by striking the projecting part of the object that lacked support underneath (Knight, 2019: 10). When sufficiently cooled, the object tended to bend after each hit rather than break (Fig. 5, e-f).

2.2.3. *Cutting with an axe*

The bronze axe (A 1) was used in three experiments. The sickles were held and shifted with pliers. The blows were more effective when the

Fig. 4. Toolkit used for the fragmentation experiment.

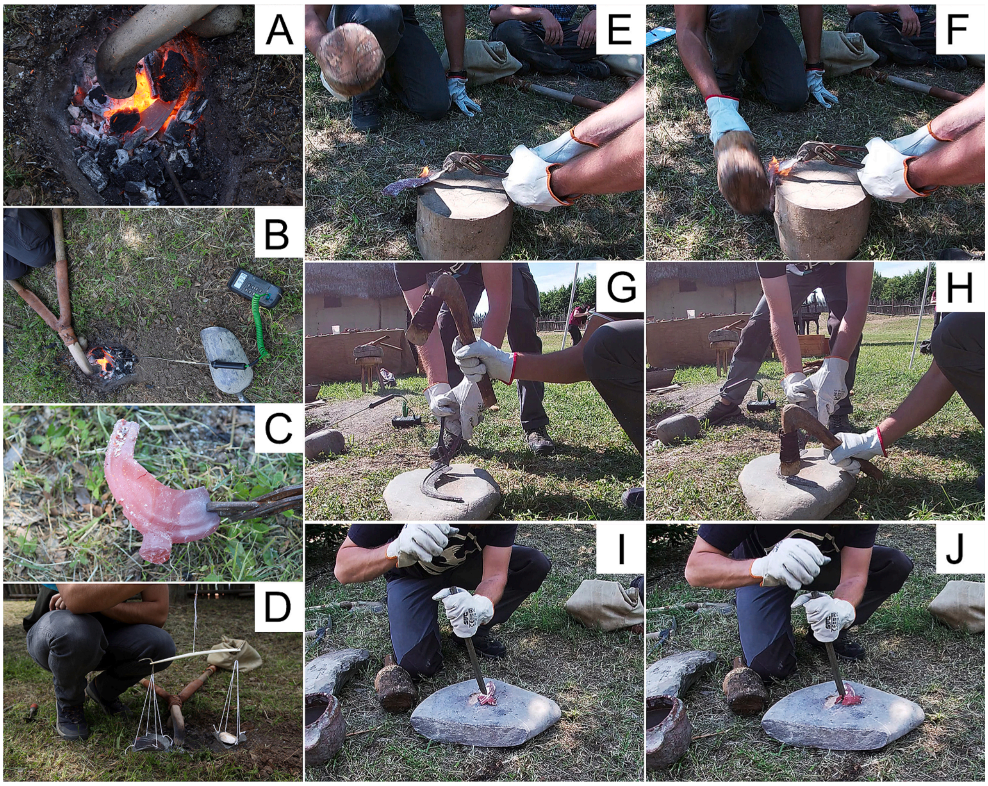

Fig. 5. Fragmentation experiment stages. a-b. heating of bronze sickle and temperature detection in the pit; c. removal of heated sickle from the pit and fragmentation with three possible methods: e-f; hammering; g-h. hitting with an axe; i-j. chiseling; d. weighing experiment.

part hit by axe was not in contact with the stone anvil, but rather the space left between the sickle and the anvil. Later on, when the object was still too hot (Fig. 5, c), each axe blow would generate more fragments. The technique was successfully performed on sickles with both low and high tin content (Fig. 5, g-h).

2.2.4. *Chiseling*

Three different chisels were used in combination with hammers to perform indirect percussion. To reduce the rebound effect, the sickle was hit by avoiding a perfectly perpendicular angle, but rather by angling the direction of the chisel in order that its cutting edge was oblique in relation to the sickle. Many fragments were obtained by hitting a replica shortly after it was removed from the fire pit. As in the other experiments, sufficient cooling of an object made it increasingly difficult to break. However, even when it was not hot enough to be easily fragmented, it was still possible to leave indentations to facilitate subsequent fragmentation after reheating. We found that the most effective approach was a combined use of chiseling and hammering. The chisel was used to make indentations and deep grooves on the surface of the sickle, while the hammer was used to inflict the final blows in order to break up the sickle through direct percussion. This technique was successfully performed on sickles with both high and low tin content (Fig. 5, i-j).

2.2.5. *Weighing sickle fragments with equal arms balance scales*

After each experiment, the fragments were weighed using equal arms scales. One pan was filled with a stone weight on which the fragmentation attempt was based (10, 20, 40, 80 g), while on the other we placed the sickle fragment (Fig. 5, d). The correspondence (or lack thereof) between fragment and stone weight was based solely on the observed balance scale inclination. When the beam was horizontal – or perceived to be so – we recorded the weight-regulated fragmentation as successfully accomplished. These data were recorded on forms filled by the performers of the experiment. After weighing with a digital scale, it was possible to calculate a tolerance range in the weighing process with equal arms scales (§ 3). Therefore, the purpose of weighing with the balance scale replicas was to assess the accuracy of these instruments, the latter being verified by weighing with a modern digital scale. Consequently, the final part of our research was conducted in the laboratory, where both ‘voluntary’ and ‘unwanted’ fragments were weighed. This dataset was further analyzed by statistical means (The experimental protocol is summarized in Fig. 6).

2.3. *Methods: The statistical analyses*

2.3.1. *Descriptive statistics and the dispersion index*

To describe the data distribution, we used three methods: Box-and-Whisker Plot, Frequency Distribution Analysis (FDA) and Kernel Density Estimation (KDE). Given a numerical data distribution, a Box-and-Whisker Plot divides it into three intervals (quartiles). The first and third quartiles contain the smallest and highest values respectively, falling below and above the box, within the whiskers. The box itself represents 50% of the data, while a horizontal line indicates the median value. Outliers fall below and/or above the whiskers, plotted as dots. This type of graphical visualization aids observation of the overall data spread.

FDA is a statistical method used to organize and visualize numerical data (Vanpool and Leonard, 2011: 20-28). Data are grouped into ranges of values each of the same size (bin). The results are plotted on a histogram showing a value scale (the weight, in this case) on the x-axis and the frequency of the occurrence of certain values (count of observations) on the y-axis. The concentration of data into specific bin(s) is highlighted by the presence of peak(s). This method is useful for identifying value concentration(s), possibly giving hints for presences of multiples of values. In the case of this research, we expected to find a peak in correspondence of each weight target value (10, 20, 40, 80 g).

As an integrative method complementing the FDA, we used the Kernel Density Estimation (KDE). In taking a set of numerical data, this

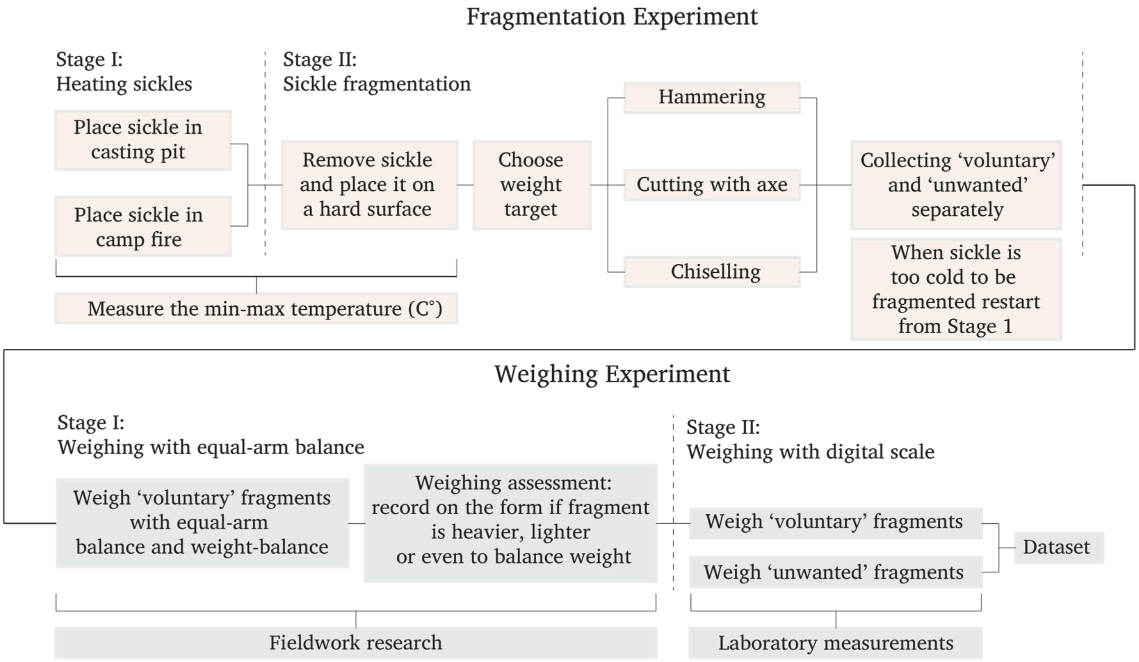

Fig. 6. Protocol of fragmentation and weighing experiment.

method provides a probability density estimation. It is possible to plot a smooth distribution curve where the 'smoothness' is highly customizable by setting the bandwidth. The higher bandwidth is, the smoother the curve appears. We used the KDE to better show the overlaid weight distribution of fragments, setting the bandwidth to observe the same peaks highlighted by FDA.

Some values and indexes describe data distributions. The arithmetic average value (mean, μ) in a normal distribution is close to the peak and it is possible to calculate the dispersion of values around the mean (standard deviation, σ) (Drennan, 2009: 29-32). A low standard deviation value indicates a high concentration of data around the mean. The same index can be expressed in relative terms with Coefficient of Variation (CV), i.e. the ratio between σ and μ: CV = σ/μ*100%. Archaeological research has often used a low CV value to confirm the occurrence of standardized production (see Ialongo et al., 2021 on the production of balance weights:; Roux and Harush, 2022 on the production of vessels). In the present study, the CV has been used as a dispersion index of weight fragments to assess the accuracy – and possibly standardization – of fragmentation.

2.3.2. In search of a metrological system: The Cosine Quantogram analysis and Monte Carlo test for significance

The FDA is particularly useful at identifying clusters and multiples of values, aside from allowing for comprehensive observation of the sample distribution. It is, however, insufficient for evaluating whether a basic unit exists or not and – if it exists – whether it is significant or not. For this reason – at least in recent years – the FDA has been frequently integrated with the Cosine Quantogram Analysis (CQA), a method originally presented by the statistician D. G. Kendall (1974). The CQA has already been used in several metrological studies (Petruso, 1992; Pare, 1999; Hafford, 2012; Pakkanen, 2011; Ialongo et al., 2018; Ialongo, 2019; Ialongo et al., 2019; Ialongo and Lago, 2021; Ialongo et al., 2021; Hermann, 2022; Poigt, 2022):

$$\phi(q) = \sqrt{2/N}\sum_{i=1}^{n} cos(\frac{2\pi\varepsilon_i}{q}) \tag{1}$$

Given a sample – where N is the sample size – all values are divided for a series of quanta (e.g. 8; 8.02; 8.04; 8.06; 8.08; etc.). Each measure (in this case the weight of each fragment) is divided by a quantum (q), rendering the remainder (ε) as a result. This remainder is tested with Kendall's formula (1). When negligible, i.e. close to 0, the result is positive. The φ(q) value indicates the sum of results of the statistical test for each tested quantum. The φ(q) value of a quantum could be either a positive or a negative number. The best quantum has the highest φ(q) value and – in a metrological system – indicates the most probable basic unit (or multiples). When plotted on a line graph with the scale of quanta on the x-axis and φ(q) values on the y-axis, it is represented by the highest peak of the 'Quantogram' (we used the open access spreadsheet from the supplementary content of the online version of Ialongo, 2019). Since the CQA gives false-negative results for measures smaller than the quanta (Ialongo and Lago, 2021: 5-6) and the sample must be composed of measures of the same magnitude (Ialongo and Rahmstorf, 2019: 118), the dataset must be prepared in advance. This can be done either by discarding measures from outside of a certain range or splitting them into several groups of measures where ranges can be partly overlapping. In the case of actual BA sickle fragments and the experimental fragments, the range value 7–200 g allowed for the testing of most samples. However, false positive results can emerge from the CQA (Kendall, 1974). To evaluate the significance of the analysis, we used Monte Carlo test assuming as a null hypothesis that the sample is randomly constituted (Ialongo and Lago, 2021). We created 100 samples of archaeological fragments and experimental ones by randomizing each measurement with ± 15% and analyzing each sample with the Kendall formula (1). We set a threshold (α) to 5%, implying that if more than 5% of random samples have a higher φ(q) value of actual sample, it cannot be excluded that the actual sample is randomly constituted. Otherwise, the null hypothesis is rejected, implying that a positive result is unlikely due to chance. This significance test has been widely applied in metrological studies in support of the CQA (e.g. Kendall 1974; Pakkanen 2011; Ialongo 2019).

3. Experimentation on fragmenting and weighing: Results

The three tested methods (hammering, cutting with an axe and chiseling) were all effective at breaking up the heated sickles (Fig. 7). The most efficient way to produce as many fragments as possible before the sickle become too cold to be broken easily was the axe-hitting method. The axe is light and easy to handle, allowing strong and

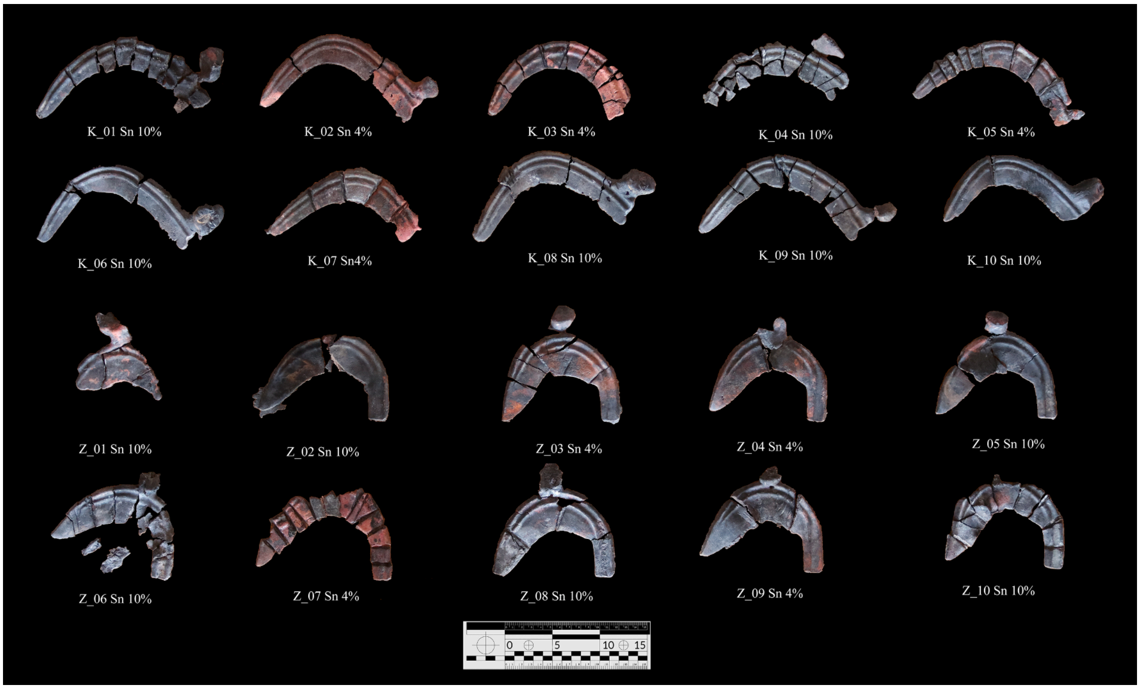

Fig. 7. Results of the fragmentation experiment.

quick blows before the object cools down. However, probably due to the experimenters' poor skill in handling the axe, the blows were not very precise, resulting in a set of inaccurate fragments. The hammering method is a more effective way to get premeditated fragments, requiring a lower number of blows. In any case, once the object cooled even slightly, breakage became increasingly difficult. Finally, the combined chiseling-hammering method ended up being the best compromise between effectiveness, rapidity and precision. Overall, the percentage of tin content influenced the breakability of an object. Sickles with a low tin content were more resistant to breaking since a higher temperature is necessary for breaking them and thus often requiring more heating cycles and blows than those with a high tin content. We tried to obtain fragments whose weights could be multiples of the theoretical unit of c. 10 g. After a short process of trial and error (repeatedly weighing fragments as soon as they were detached from the replica), we became skilled enough to roughly predict the mass of the fragment. As our experiment proceeded, it became soon clear that the fragmentation process could not be entirely controlled. The act of fragmentation, in fact, often produced random and 'unwanted' fragments, i.e. ones accidentally detached after hitting; casting cones; pieces molten and detached in the forge and the terminal pieces. These were recorded as 'unwanted'. As it turned out from the weight analysis, the weight values

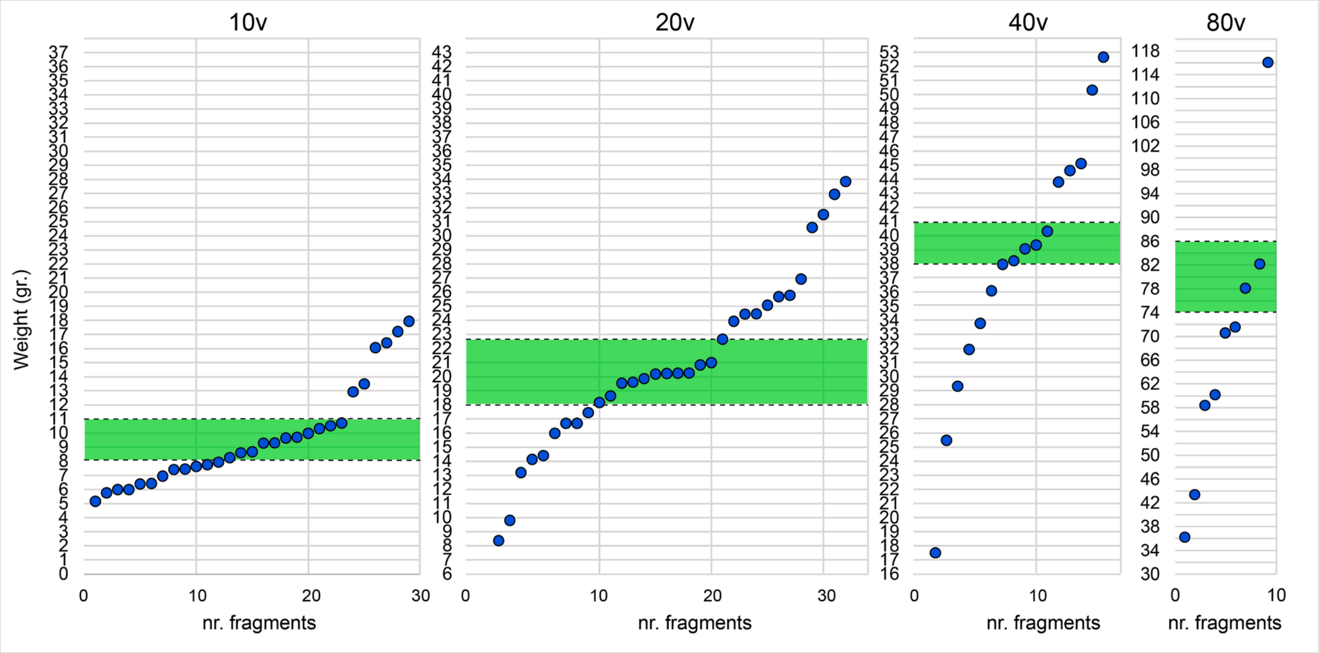

Fig. 8. Results of the weighing experiment: range of tolerance of equal arms balances. Under the green band are the fragments estimated as 'correct' after experimental weighing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of these ‘unwanted’ fragments is completely unpredictable. They are usually light, populating the left side of the histogram. All the other pieces, voluntarily obtained, were recorded as ‘voluntary’ fragments. From an amount of 138 fragments, we counted 51 ‘unwanted’ (37%) and 87 ‘voluntary’ (63%) pieces. As a result of the weighing operations with the equal arms balance scale, only a limited number of ‘voluntary’ fragments complied with the balance weights. Once weighed with a digital scale, the fragments evaluated as consistent with the balance weights could be inscribed within a range of tolerance of ∼ 10–15% from the ideal mean (Fig. 8).

4. Describing the sample: Results of Box-and-Whisker Plot and Frequency distribution analysis

Since we collected the ’unwanted’ and ‘voluntary’ fragments separately, it has been possible to discern the two datasets. ‘Voluntary’ fragments can be divided into four different distributions, corresponding to the four weight targets (10, 20, 40, 80 g). The Box-and-Whisker Plot shows that the dispersion of weight values around each target was directly proportional to its size: the higher the value, the wider the weight dispersion. The error is equally dispersed between higher and lower values and the median value is quite close to the desired weight (Fig. 9). Instead, the fragments obtained by attempting to produce pieces weighing 80 g are too few to expect an accurate average value as well as for more detailed statistical analysis. The FDA built on 10, 20 and 40 g increments shows the peaks as slightly lower than the target values (Fig. 10). It is our understanding that ‘voluntary’ fragments are slightly lighter than expected, i.e. during the experiment we overestimated the weight of sickles, producing fragments slightly smaller than necessary each time. The CV of voluntary fragments is around 30% (Table 2), a value that could be considered high when compared with the commonly accepted error of balance weights, estimated around 4–6% (Cardarelli et al., 2004, Rahmstorf, 2010, Ialongo et al., 2021).

‘Voluntary’ and ‘unwanted’ fragments were plotted together on a histogram showing both the peaks corresponding to some desired values and the influence that randomly obtained fragments (i.e. ‘unwanted fragments) have on the sample (Fig. 10, a). The statistical background noise generated from the latter does not prevent the recognition of clusters of values. Furthermore, most values are concentrated on the left part, both because of the major attempts aimed at 10 and 20 g fragments and also because of the right-skewed distribution of ‘unwanted’ fragments (Fig. 10, c). Two main clusters of values are concentrated around 10 and 20 g, clearly because of the ‘voluntary’ fragmentation. Random peaks emerge between ‘voluntary’ distributions, where right tail of the former and left tail of the latter overlap. It is our understanding that random values can potentially influence the results of the analysis. However, as the number of data increases, this risk would probably have decreased. Due to limited resources and time, in comparison to objects retrieved from archaeological contexts, the analysis of experimental fragments relies on a rather small dataset.

4.1. Cosine Quantogram analysis: Results

The whole dataset (including ’unwanted’ and ‘voluntary’ fragments) was tested by applying the CQA method, limited to the fragments within a range from 7 to 200 g (117/138 fragments). This emphasizes a peak of values around c. 8.6–9 g (Fig. 11, d). The best quantum does not exactly fit with the chosen basic unit of 10 g, while it is relatively consistent with FDA peaks and the general overestimation of weight occurred during the experiment (Fig. 10, a-b). Therefore, the highest peak is clearly due to the intentional and supervised fragmentation, and the high number of ‘unwanted’ fragments randomly distributed does not prevent this observation. However, contrarily to what has been observed for archaeological fragmented sickles (§ 1.2), the result of the CQA of the

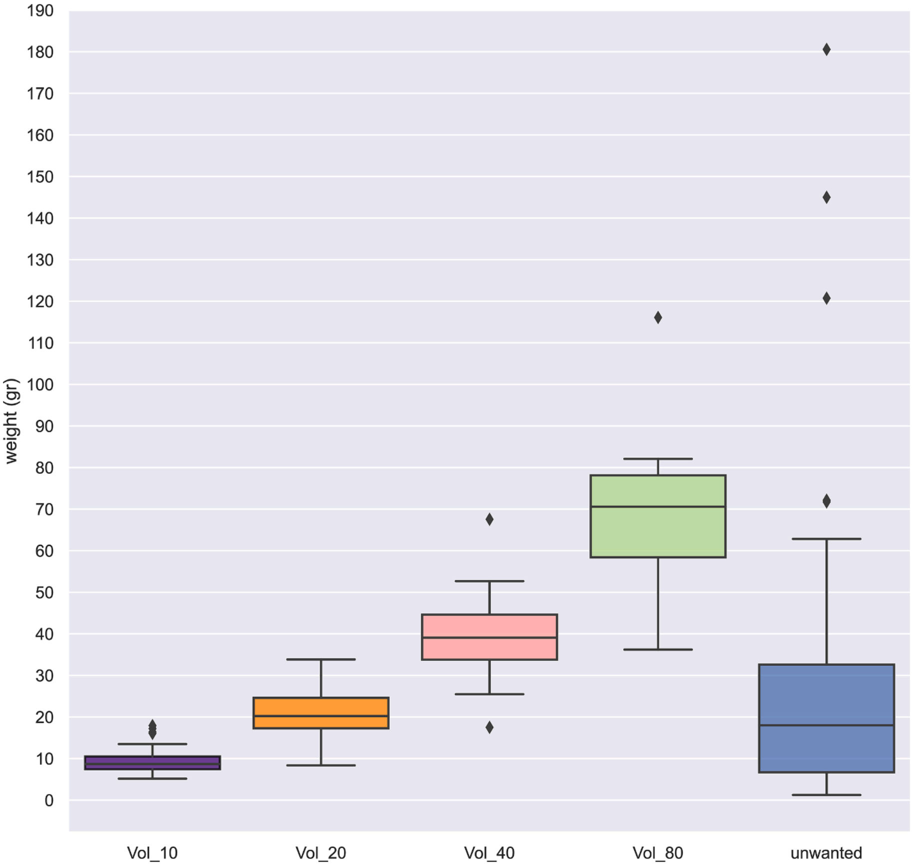

Fig. 9. Box-and-Whisker Plot of ‘voluntary’ fragments. Vol_10 = 29 fr. Vol_20 = 32 fr. Vol_40 = 17 fr. Vol_80 = 9 fr.; ‘Unwanted’: 51 fr.

Fig. 10. A. fda of 'voluntary' fragments; b. kde of 'voluntary' fragments (87); c. fda of 'unwanted' fragments; d. kde of 'unwanted' fragments.

experimental fragments does not overcome the threshold (α) of significance, set to 5%. Since the experimental fragments do not pass the significance threshold, the null hypothesis cannot be rejected. Theoretically speaking, if we treat an experimental sample the same as an archaeological one, we would have concluded that fragmentation may have occurred by chance, and the CQA yielded a false positive result. Instead, since we conducted the experiment ourselves and know that observed peaks of FDA are not (all) random (Fig. 10 a) and the CQA results are coherent with the FDA peaks, we should attribute the results of Monte Carlo test to other variables. It is probably due to the low number and precision of 'voluntary' fragments, along with the relatively high share of 'unwanted' fragments and, more generally, the 'small' size

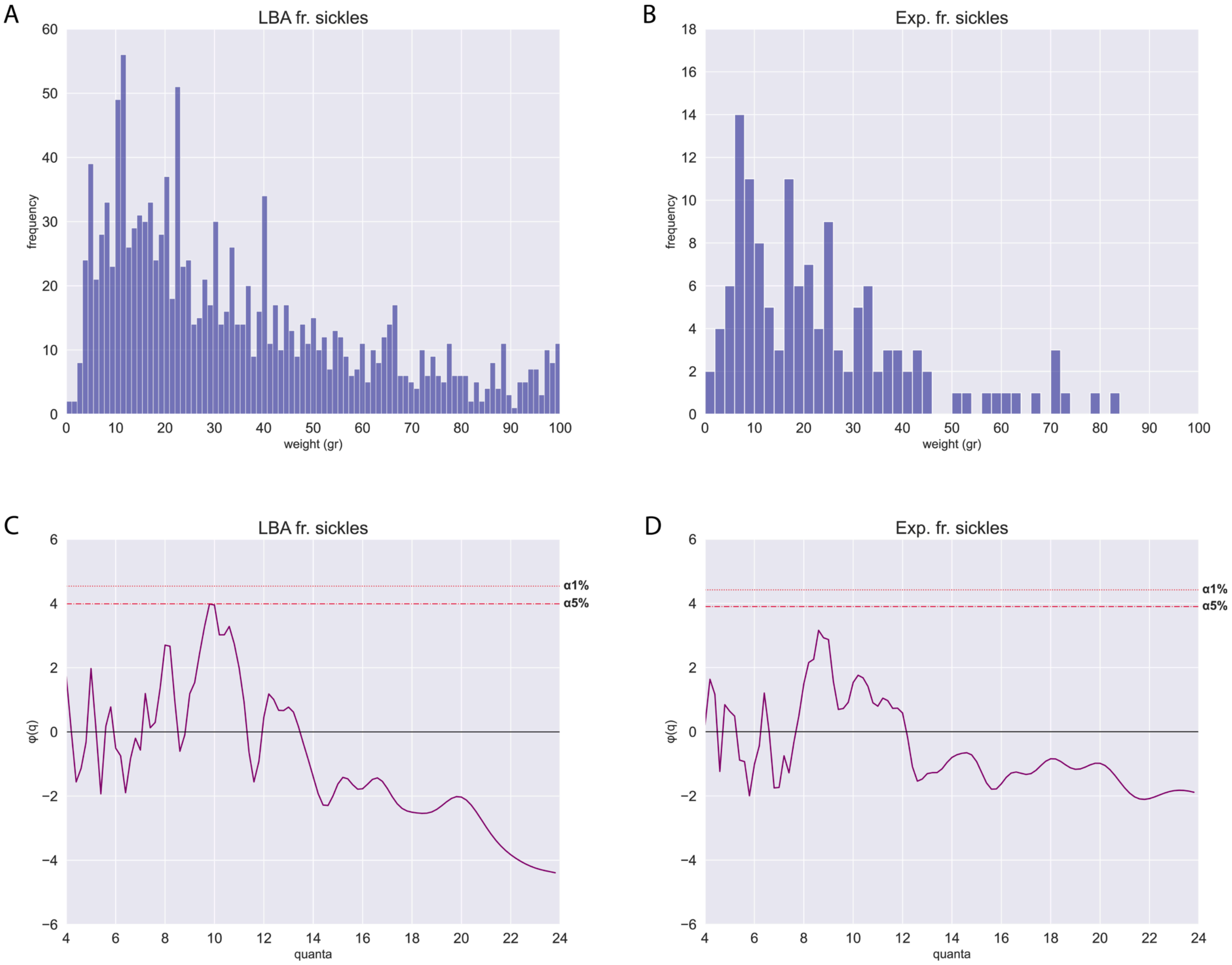

Fig. 11. A. fda of archaeological fragmented sickles (1533); b. fda of fragments from the experiment (138); c. CQA and Monte Carlo test of archaeological fragmented sickles (1422/1533); d. CQA and Monte Carlo test of fragments from the experiment (117/138). The dataset from the experiment includes both 'voluntary' and 'unwanted' fragments.

Table 2
Number, mean, median, standard deviation and coefficient of variation of 'voluntary' and 'unwanted' fragments.

	no. of fragments	weight mean (μ)	median	standard deviation (σ)	Coefficient of Variation (CV)
10 vol	29	9.65	8.68	3.56	36.90%
20 vol	32	21.03	20.23	6.15	29.20%
40 vol	17	39.59	39.07	11.3	28.50%
80 vol	9	68.51	70.59	23.45	34.20%
unwanted fr.	51	28.69	19.56	35.47	123.60%

of the sample. A sample sizes of 117 is probably insufficient for a reliable result using the CQA (Kendall, 1974: 233; Çankaya and Fieller, 2009: 379), while the sample size (1422) of archaeological fragmented sickles certainly is for the proposed analysis. This disparity in the sample size between experimental and archaeological fragments makes comparing the results of statistical analyses more difficult.

5. Discussion: Comparing archaeological and experimental results

As the experiment has shown, breaking up bronze objects like sickles is a relatively easy process, requiring a very limited set of tools and a campfire. Rough weight-based fragmentation is possible even for persons with poor or no metalworking skills, but some skill can probably enhance the accuracy of the fragmentation, resulting in fragments within the desired range of weight and probably less 'unwanted' examples. During the Late BA, the existence of a Pan-European weight system to refer to probably made the bronze fragmentation a well-codified action related to the economic exchange of currencies and goods, and an easily replicable process among the communities.

The comparison of histograms derived from experimental and archaeological sickle fragments shows that both share the approximately right skewed shape, where most of the data comes to lie in the left part of the distribution, i.e. most fragments are light compared to the supposed standard. Experimental fragments show a multimodal distribution with various peaks approximately at the multiple of base units, along with some random peaks. The same thing can be observed in several weight histograms of archaeological Late BA fragments (Sommerfeld, 1994: Fig. 5; Ialongo and Lago, 2021: Fig. 10) and archaeological fragmented sickles (Fig. 11, a-b). The CQA regarding experimental fragments, despite the small size of sample, seem to confirm the efficacy of the analysis in detecting the presence of a basic unit in numeric data distribution, even when the dataset has a conspicuous presence of random values. In general, we assert that the results of the experimental dataset correspond convincingly with the results of the archaeological fragments, lending plausibly to the hypothesis of the weight-based fragmentation in the European Late BA. The experiment discussed in this paper shows that the repeated action of fragmenting bronze to obtain pieces of certain weight is detectable with methods of descriptive statistics and CQA. Statistics allow for detecting the attempts to make weight-regulated pieces even in case of imprecise fragmentation. Based on the comparison of statistical results, archaeological Late BA fragments and experimental fragments seem to share similar metrological characteristics.

Even though the research presented here does not include any traceological studies, the experiment has provided us with a useful reference collection of fracture marks that can be used in various future studies which compare them with archaeological specimens. Indeed, in spite of ever-increasing knowledge of BA fragmentation techniques and diffusion of the phenomenon, studies of macro- and micro-traces on archaeological fragments remain a *desideratum*. Future research on these aspects would shed new light on bronze fragmentation techniques and purpose.

6. Conclusion

The data support the hypothesis that at least some of the archaeological bronze objects were fragmented according to a weight standard, which is consistent with existence of Pan-European weight systems. While the high share of 'unwanted' fragments resulting from experiment is partly due to lack of skill on the experimenters' part, the nature of the particular fragmentation method is such that even skilled metalworkers would have produced some 'unwanted' fragments, though certainly fewer than unskilled individuals. The fragments found in European BA hoards may be interpreted as collections of both 'voluntary' and 'unwanted'. However, since bronze was a valued commodity and the quantity of metal could be easily measured with weighing tools, it was not necessary that all metal pieces were weight-regulated. Small fragments could have been added or subtracted to the balance pan till the intended quantity for trade was reached. However, pre-weighed fragments (i.e. money) would have sped up the transactions (Ialongo and Lago, 2021: 9).

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CRediT authorship contribution statement

Giancarlo Lago: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition, Visualization, Investigation. **Matteo Cianfoni:** Writing – review & editing, Visualization, Investigation, Resources. **Federico Scacchetti:** Investigation, Resources. **Luca Pellegrini:** Investigation, Resources. **Andrea La Torre:** Investigation, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The following are the Supplementary data to this article:

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Appendix A. Supplementary data

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