Heritage Science

RESEARCH

Exactly how free? Constrained choices and product ranges of medieval copper-alloy objects found between the Meuse and Loire rivers (9th–16th centuries CE)

Lise Saussus[1,2,5*], Nicolas Thomas[3,4] and David Bourgarit[5,6]

Abstract

This contribution synthesises the PIXE and ICP-AES elemental analyses carried out on a large dataset, comprising of 300 copper-alloy objects dating mainly to the Late Middle Ages. The objects are drawn from heritage institutions and archaeological contexts in various regions between the Meuse and the Loire rivers (France and Belgium). This investigation focuses on the main elements that make up the alloys (Cu, Zn, Sn, Pb). Past studies have often defined the composition of an alloy as an intentional choice, however in this paper we aim to identify the constraints in alloy manufacture in a bid to understand the degree of freedom enjoyed by craftsmen during this period. We will also evaluate to what degree the constraints imposed by technique, economic conditions and social requirement, affected production in a complex multifactorial system. We have opted to define alloys by object type, functional area and social context, by chronology and product ranges. For cast table- and the kitchenware, we have observed that alloys and the objects are standardised on a trans-regional scale. Conversely, the hammered objects are produced with a greater freedom, leading to a new hypothesis regarding specific workshop practices. Finally, we will propose a predictive model for cast objects that we hope is better suited for the study of heritage objects, their materials and their production processes, to be verified in future studies. This approach emphasises the importance of considering everything that makes an object what it is: its function, status and place in the market, when researching heritage materials.

Keywords Copper alloys, Bulk analyses, Constrained choices, Product ranges, Material culture, Late Middle Ages, North-Western Europe

*Correspondence:
Lise Saussus
lise.saussus@uclouvain.be
[1] DIM-PAMIR, Centre de Recherches Historiques-EHESS, Paris, France
[2] F.R.S.-FNRS National Fund for Scientific Research, Centre de Recherches d'archéologie Nationale, UCLouvain, Ottignies-Louvain-la-Neuve, Belgium
[3] INRAP, Institut national de recherches archéologiques préventives, Paris, France
[4] UMR 8589 Laboratoire de médiévistique occidentale de Paris, Centre National de la Recherche Scientifique (CNRS), Université Paris 1 Panthéon-Sorbonne, Paris, France
[5] Centre de Recherche et de Restauration des Musées de France, Paris, France
[6] UMR 8068 TEMPS (Technologie et Ethnologie des Mondes Préhistoriques), Centre National de la Recherche Scientifique (CNRS), Université Paris Nanterre/Université Paris 1 Panthéon-Sorbonne, Paris, France

Introduction

Copper-alloys were a significant part of the material culture of Late Medieval North-Western Europe, as evidenced by archaeological, written and iconographic sources [1]. A greater demand for these objects, particularly for the table, kitchen and dress, and an increase in production occurred from the 13–14th centuries onwards [2]. They finally became staples from the 14th to early 16th centuries in different contexts of use, for instance for dress accessories and other small personal items [3, 4], harness ornaments [5], domestic utensils [6], artillery [7], shops or urban industries, for instance the dyers' or brewers' tanks, or even bells for churches and belfries, roofs and other monumental works [8].

Contributions have focused on the alloys of High or Late Medieval objects in England [9–14] and Wales [15], Germany [16–22], and more recently in Al-Andalus [23]. For the area between the Meuse and the Loire, there are still too few published studies devoted to the analysis of metal composition, with only rare papers on ecclesiastical items [22, 24], or specific objects: [25] a fountain, [26] candlesticks, [27] seals, [28] canons, or workshop waste [29–31]. Over the last fifteen years, several Franco-Belgian research projects have focused on a significant number of objects dating between the 9th and 16th centuries, mainly from contexts of use, discovered during preventive excavations. The corpus of 300 items includes household equipment and various furnishings, liturgy, church ornaments and devotional objects, merchants' items and astronomical instruments. This paper proposes a synthesis of their analysis. It focuses mainly on the contents in main elements (copper, tin, zinc, lead), but some attention will be paid to the impurities during discussion about the quality of the alloys.

These analyses lead to question how to interpret the compositions. Whatever the context, when discussing the alloy composition, most archaeometallurgical studies consider composition as the result of choice [32–35]. It is sometimes even described as "an intentional action determined by human choice" and the result of "a deliberate choice of alloying elements" [36–39], or of an "alloying strategy" [9, 29], referring to an intentional action determined beforehand. At first sight, this way of discussing the composition of an alloy may not be wrong depending on the context and the objects, but it pushes aside the possibility that the degree of freedom may not be as great as commonly accepted.

This paper aims to address the following questions for medieval North-Western Europe: is the composition of an alloy the result of an individual choice made by the artisan, a strategy applied by a specific workshop, or rather the result of the entanglement of a set of constraints (technical, economic, social…) imposed on them? For example, the low lead content in hammered copper alloys is a well-known technical constraint, as the addition of lead limits the metal's ductility. In other words: what degree of freedom does the craftsman have in producing an alloy? And how does a well-documented intense recycling at this period contribute to the discussion [38, 40]? Far from focusing only on the metal itself, this study considers the object in its entirety, as a source of meaning. This paper explores several product ranges and examines the link between alloy type, manufacturing technique, production process, functional area, social context of use, and chronology for objects representative of Late Medieval material culture, focusing on the area between the Meuse and Loire rivers.

A large corpus from 9th to 16th centuries

The corpus comprises 300 mainly unpublished objects and fragments of which almost 75% come from 54 archaeological sites. The remaining objects are from the collections of 10 museums that have provided coherent sets of objects that are rarely found during excavation. Most archaeological sites are located in the Meuse and the Seine Valleys and in and around Flanders, completed with a few excavations in the Vendée, Lorraine and the Marne (Fig. 1). These artefacts ($n=230$) come from urban settlements (116 objects), rural sites (50), castral contexts (52), abbeys or priories (7), and the dredging of the Meuse river (5). Contexts, such as rivers (Valenciennes-Cœur de ville), wells (Château de Logne), or barrels (Raversijde, near Ostend) provided large assemblages. Other contexts such as Rodemack or Bezannes also contributed with a significant number of objects due to the use of a metal detector during excavation. Elsewhere, the discoveries are more scattered, such as in Douai, where seven settlements provided a few objects each, for a total of 23 items.

The set is composed exclusively of copper alloy objects from contexts of consumption. It, therefore, excludes workshop waste. These are medium-sized objects from households, shops, churches or castles. Household items represent ¾ of the study ($n=217$, Fig. 1), their uses were identified finds context and comparison with iconographic and written sources [41, 42]. These include cooking implements (30 tripod cauldrons, a frying pan, two lids including one undefined, 14 skimmers, and a milk filter), implements for cooking or hygiene (15 kettles), for hygiene or the table (eight basins, eight ewers, four lavabos used to pour water into the basin or a stone lavabo), tableware (31 spoons, two stoves, 75 candlesticks, excluding those from liturgical and devotional contexts). Furthermore, 26 vessels were undefined but could have been used for cooking, hygiene or as tableware. A separate category consists of 29 repairs either isolated or

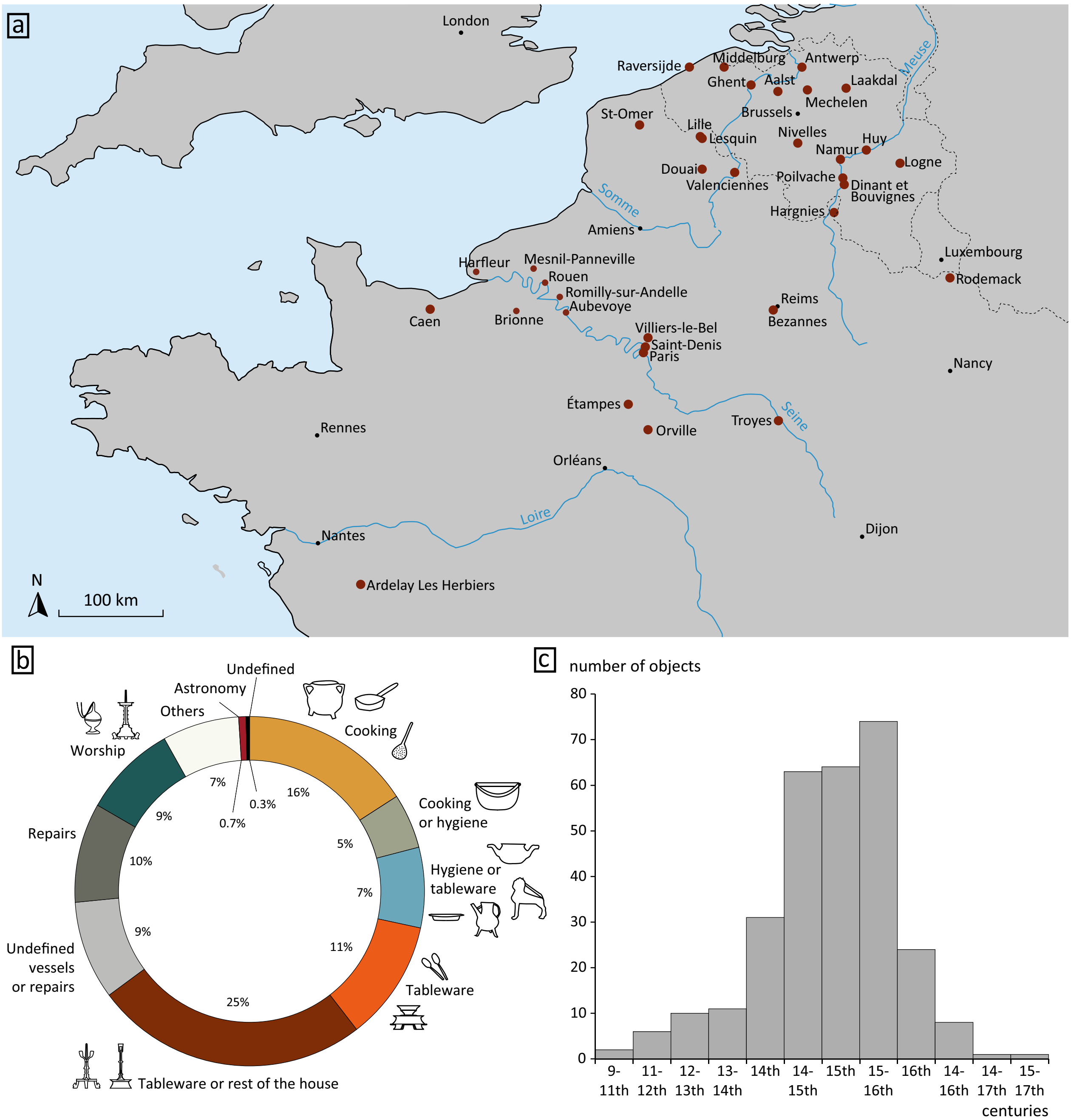


Fig. 1 **a** Location of the archaeological sites providing the analysed objects ($n = 230$): 116 objects from 36 urban settlements (Aalst, Antwerp, Bouvignes, Brionne, Dinant, Douai, Etampes, Ghent, Harfleur, Huy, Lille, Mechelen, Namur, Rouen, Saint-Denis, Saint-Omer, Valenciennes), 50 objects from 7 rural housings (Aubevoye, Bezannes, Laakdal, Lesquin, Mesnil-Panneville, Romilly-sur-Andelle, Raversijde), 52 objects from 8 castles or fortresses (Ardelay-les-Herbiers, Caen, Orville, Hargnies, Logne, Middelburg-in-Vlaanderen (Maldegem), Poilvache, Rodemack), 7 objects from 3 abbeys or priories (Nivelles, Romilly-sur-Andelle, Villiers-le-Bel), and 5 objects from dredging of the Meuse river (Dinant – Meuse). **b** distribution of the analysed objects by functional category. **c** distribution of the analysed objects according to chronology. CAD: Lise Saussus

found on vessels potentially made from a different metal. In two cases involving small fragments, it was impossible to determine if they were the sheet metal from the vessel itself or from the repair.

28 other objects are related to cult activities (16 statuettes and an osculatory, five censers, two altar candlesticks, a chalice, a ciborium, and a basin) or to the

funerary sphere (an engraved funerary plate, ML-PL[1]). The context of the discovery of a basin (NGP-B) in a tomb in the cemetery of the abbey of Nivelles links the object to the sacrament of hand-washing. 21 other objects can be classed as miscellanea were used for various functions that are not always possible to link to a precise social context of use, such as measuring instruments (two scales, one nest), a mortar, 15 taps, a wind-vane (ORV-G)[2] and a door knocker. Two astronomical instruments (an astrolabe and a portable sundial) enrich this diversified corpus. Finally, a statuette representing a court jester cannot be classified in the previous categories. Items for body adornment, such as dress accessories or harness ornaments are excluded, forming a separate class of objects that weigh only a few grams and whose production differs from that of medium-sized items. At the other end of the scale, cannons and bells are excluded from this study for the same reason.

Relating to the technical aspects, 54% of the objects, the majority of which weigh from a few tens of grams to a few kilograms, are manufactured by casting (by pouring metal into a mould). Nearly 34% of the objects are shaped by plastic deformation. The remaining 12%, the 31 spoons, are produced by combining the two techniques: the handles are probably made by casting and the form and thickness of the bowl obtained by hammering. Most of the objects are dated from the beginning of the 14th century to the 16th century (Fig. 1). The oldest item is the hand basin from the abbey of Nivelles, dating to the 9–11th centuries. Archaeological context or analogy with other objects provide the dating that remains imprecise for some items. It should be noted, however, that some objects are difficult to date by their shape, for example, tripod cauldrons changed very little between the 13th and 16th centuries.

Methods

Elemental composition analyses

Of the 300 objects of the corpus, 438 bulk composition analyses were carried out. The difference between the number of objects and the number of analyses is because the same object can consist of different parts that were individually analysed. Three minimally invasive techniques were used: µ-beam Particle Induced X-ray Emission (PIXE, $n = 236$), inductively coupled plasma atomic emission spectrometry (ICP-AES, $n = 197$), and Energy Dispersive X-Ray Spectroscopy on scanning electron microscopy (SEM–EDS, $n = 5$).[3] The low sensitivity of SEM–EDS allowed only the quantification of main elements. Of the total 438 analyses, 19 are ICP-AES replicas of PIXE analyses to compare the results obtained with the two methods for 12 objects (cf. below).

Most objects were analysed at the Centre de Recherche et de Restauration des Musées de France (C2RMF) using one of the two usual techniques for copper alloy analysis, PIXE or ICP-AES. If the objects were too small to take samples or when sampling was not permitted, PIXE was used instead of ICP-AES. The PIXE analyses, using the AGLAÉ and NewAGLAÉ (since 2017) accelerator facility, were carried out directly on the objects after abrasion of the corrosion layer to reach the preserved bulk metal. The analyses of certified reference materials (CRMs) representing a variety of copper and copper alloys compositions were carried out at the beginning and the end of the analysis session using the same protocol. The global relative error on the measurement was estimated to be less than 5% for the main elements, except for high levels of lead (see hereafter). For more details on the method see [29].

The ICP-AES analyses were carried out with a Perkin-Elmer Optima 3000 SC spectrometer after sampling 8 to 12 mg of metal. For objects with walls thicker than 1 mm, the sample was drilled with a 0.6 to 1 mm diameter drill (HSS or WC). For thinner objects, a circa $4mm^2$ sample was cut from the surface when possible (else PIXE was carried out instead of ICP-AES). After cleaning and precise weighing, the samples were digested in *aqua regiae*. The CRMs were prepared exactly the same way, including drilling. For more on the protocol, see [43]. The overall error on the measurement including weighing, calibration, and instrumental errors is estimated to be about 10%.

Although the two techniques used at the C2RMF, PIXE and ICP-AES, have long been proven to yield consistent results (notably through the systematic analysis of CRMs), we took the opportunity to carry out a small comparison for 12 objects, by analysing them using both techniques (19 replicas of the total 438 analyses, Fig. 2). Whereas the zinc contents align almost perfectly with the "PIXE = ICP-AES" line, tin is slightly overestimated by PIXE probably due to tin-enrichment in the upper layers of the metal (with our operating conditions, a surface layer of only circa 50 µm thick is scanned by PIXE thus rendering the technique sensitive to any surface chemical segregation). The lead discrepancies pertain mainly

[1] https://collections.louvre.fr/ark:/53355/cl010092623 (viewed on 28/08/2022).
[2] https://archea.roissypaysdefrance.fr/collections/collection/girouette-du-chateau-dorville (viewed on 28/08/2022).
[3] SEM–EDS analyses were carried out at the Laboratoire d'analyses physiques et de caractérisation des matériaux (Direction de l'archéologie préventive, Communauté d'agglomération du Douaisis).

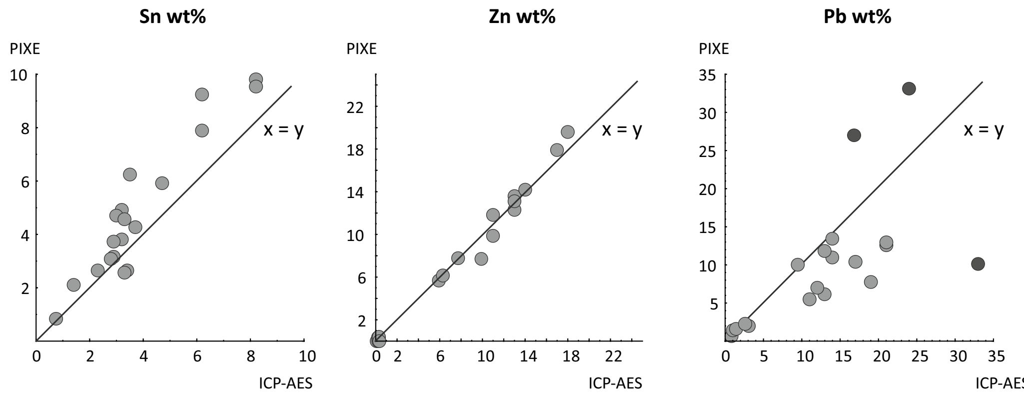


Fig. 2 Binary diagrams plotting PIXE and ICP-AES results of the main elements, in wt% ($n=19$)

to the well-known phenomenon of the uneven distribution of lead in solid copper. For the high lead contents, an additional phenomenon of macroscopic segregation may take place, as notably observed on a tripod cauldron (33% lead by ICP-AES versus 10% by PIXE): the ICP-AES sampling of one of the legs showed a high lead content perhaps due to the lead having severely migrated during casting and/or use (cooking on a fire). However, as we will see later these ponctual consistency issues do not impact the compositional groupings.

Statistical analysis

The aim of the statistical analyses is to explore the dependence between the compositions (Cu, Sn, Zn, Pb contents and sum of main impurities, i.e. Sb, As, Ag, Fe, Ni, S) and the categorical variables observed in the archaeological and technical studies of the objects (manufacturing technique, type of object, functional area, production type i.e. commissioned or serial and mass-produced items, if the object was in use before or after 1300). Zn/Sn and Zn/Pb binaries and histograms of the Cu, Sn, Zn and Pb contents distributions present a broad view of the alloy compositions (see "Alloy nomenclature" section) before the statistical analysis per se. Qualitative variables are then introduced: the shaping technique (see "Groups according to shaping technique" section), the type of object (see "Groups according to object type and functional area" section) and consequently the functional area. Ternary diagrams help to visualise the link between object type and the relative contents of Sn, Zn and Pb in the alloy. A standard 1-way ANOVA test is performed on the data (at the confidence level alpha = 1%), to check if the variable "type of object" impacts on the average concentrations in Sn, Zn and Pb. Factorial analysis of mixed data (FAMD) is performed in R [44], on the reduced centred dataset, and applied to cast objects ($n=229$), excluding cast items of undetermined function or for which the functional category is poorly represented ($n=26$). Our aim was to examine the contents of Cu, Sn, Zn and Pb in relation to three categorical variables: functional area, production mode and dating before or after 1300. Following this FAMD, a hierarchical clustering on the main components was performed (Ward's method) and a number of classes was defined according to the gain in inertia. These classes are discussed as indicative of product ranges in "Product ranges" section.

Results

Alloy nomenclature

The copper alloys have very different compositions (Additional file 1: Tables). Copper content varies from 55 to 99.9wt%, tin varies from below detection limit to almost 20wt%, zinc from almost below detection limit to 33wt% and lead content can reach 33wt%. The relative contents of these four main elements distinguish the different alloys. Copper and tin alloy is bronze, while copper and zinc alloy is brass. However, bronze may contain some zinc and brass some tin. All these alloys may contain more or less lead. Finally, copper can be unalloyed or low-alloyed when it has only a few percent of tin, zinc and/or lead. These compositions form a heterogeneous and sometimes continuous whole. In studies on medieval alloys, groups are defined on uni-, bi- and tri-variate statistical analyses. Bayley [11] proposed a boundary between brass and bronze brass along the line Zn = 4Sn (when the zinc content is greater than four times the tin content the alloy may be called brass, see Fig. 3). The boundary between bronze and red brass corresponds to Sn = 3Zn. In [29], these limits differ slightly when adapted to the corpus of small Parisian dress accessories: the brass/red brass border is located at Zn = 3Sn, and the bronze group is more extensive since it includes individuals whose tin content exceeds that of zinc (Sn > Zn). In the latter paper [29], leaded alloys were classified into

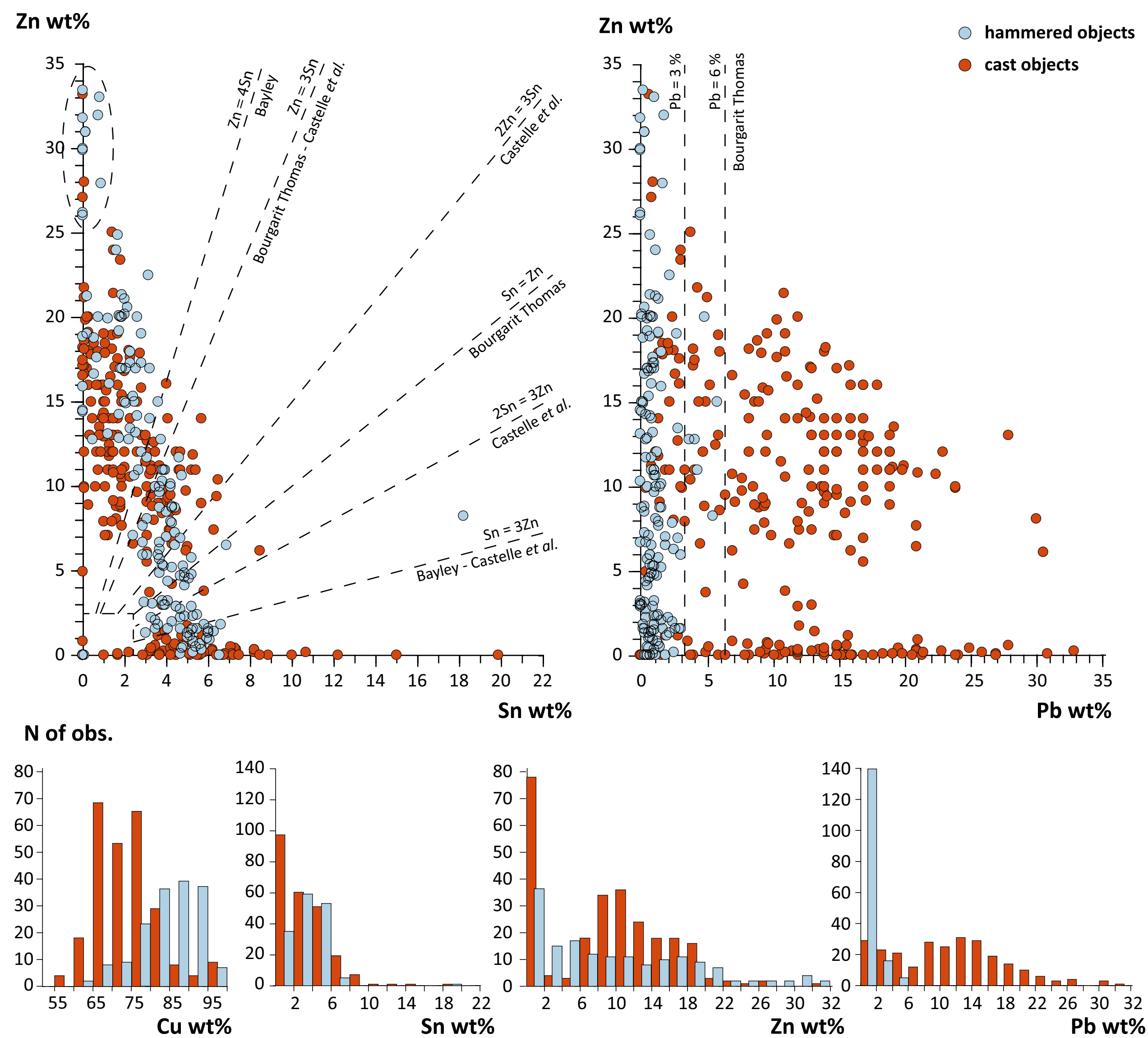


Fig. 3 Above, binary diagrams plotting the contents of zinc/tin and zinc/lead, according to the shaping technique. The boundaries between the different alloy nomenclatures are reported depending on the authors (Bayley 1991, Bourgarit Thomas 2012 and Castelle *et al.* 2020; below, histograms showing the distribution of copper, tin, zinc and lead contents, according to the shaping technique, $n = 255$ (analyses of cast objects) and 164 (analyses of hammered objects, including spoons)

two categories: slightly leaded when 3–4 < Pb < 6wt%, and leaded when Pb > 6wt%. The boundaries of [11] and [29] were partially taken up by [27] for the study of seal matrices by introducing other borders: those between Sn-rich red brass (between Sn ⩾ 3Zn and 2Sn ⩾ 3Zn), red brass (between 2Sn ⩾ 3Zn and 2Zn ⩾ 3Sn) and Zn-rich red brass (between 2Zn ⩾ 3Sn and Zn ⩾ 3Sn).

The authors of these studies have already pointed out that the proposed limits are practical tools without being universal and must be confronted with the corpus under study. In the present case, the compositions are distributed too continuously to enable any distinction between brass and red brass (Fig. 3). Nevertheless, one group stands out clearly among the brasses: zinc-rich brasses (more than 25wt%). They are almost lead-free (with some exceptions) and show less than 1wt% of tin distributed along a lognormal curve, its presence being probably unintentional. The boundary between bronzes and Sn-rich red brass proposed by Bayley [11] seems more relevant for the cast objects. The cast bronzes contain almost no zinc, the latter being unintentionally present. However, the boundary between bronzes and

Sn-rich red brass does not seem suitable for hammered objects. More generally, the continuity in the distribution of alloy compositions strongly suggests that other variables are needed to form relevant compositional groups. It is fundamental to not only consider these objects just by the metal they are made of, but as representing the supply and demand in a particular economic context. They also bear witness to the techniques used in their manufacture, they relate to a function and a social context of use. They are a receptacle of social representations that evolve over time. The manufacture, the object type, its functions, values, and chronology (Table 1) contribute to defining each alloy groups.

Groups according to shaping technique

The most apparent discriminating criterion is the shaping technique, as it distinguishes two groups according to the degree of alloying, lead content and impurities. Cast alloys (255 analysis without replicas) appear to be more alloyed than hammered alloys (164 analysis without replicas; Fig. 3). This is directly related to lead content, characterised by a lognormal-like distribution for hammered objects. The concentrations are almost always lower than 3wt%, except for some items where lead reaches 6wt%. In contrast, the lead content evolves much more continuously for cast objects up to much higher values (33wt%). For spoons, the lead content is generally below 3wt%, which tends to confirm that the final shape of the spoon is obtained by hammering. The impurity content (Ag, As, Fe, Ni, S, Sb) is lower for hammered alloys (Fig. 4): the median value is around 0.7wt% compared to 1.7wt% for cast objects. The total impurity content rarely exceeds 2wt% for hammered objects, except for the two parts of the astrolabe that were found have a higher nickel content. The sum of impurities overtakes 2wt% for cast items in 40wt% of cases. Furthermore, hammered and cast objects share similar compositions and their plots can overlap on the graphs. Some cast objects contain little lead.

Groups according to object type and functional area

As well as defining objects by the technique used in their shaping, they can be classified using other parameters (Table 1) such as the type (cauldrons, hand basins, kettles, candlesticks…), functional domain (kitchen, table, hygiene, cult…) and social context of use, for example whether the object is used in a common or more privileged strata of society. This last criteria was previously based on written, archaeological and iconographic sources [41].

The functional area and social context of use may change with time. A break in the consumption and production of copper-alloy objects is observed around the 13th century [1], mainly in terms of the quantities produced (for the cauldrons: [45]) and the uses of certain objects. For instance, the basin originally only used in liturgical or found in aristocratic contexts gradually became an object of common hygiene in most homes [46]. Candlesticks undergo a transition and become more common after 1300 [41]. The type of production makes it possible to differentiate between items produced for specific commissions (such as some liturgical candlesticks or statuettes) and mass-produced objects manufactured in large series to supply an important demand (such as cast cauldrons or domestic candlesticks from the 14th and 15th centuries). Between these two extremes, some items may have been commissioned, such as stoves or lavabos, even though a serial character cannot be excluded, as demonstrated for funerary brasses [47]. These different criteria lead to a typology of the objects that generally corresponds to weight ranges in relation to the shaping technique. Metal cast walls are systemically much thicker: a few kilos for example for cauldrons, only a few hundred grams for pans or skimmers.

To distinguish alloy groups according to the type of object, we examined the distribution of main elements and ternary diagrams plotting the contents of lead, zinc and tin (Figs. 5, 6).

We can distinguish clear groups for the most represented categories of cast objects: most tripod cauldrons are leaded bronzes (Sn 5-20wt% avg. 6,6wt%; Pb 4-33wt% avg. 15,8wt%; Fig. 7), although there are some exceptions in leaded copper, including a 12–13th-century cauldron and two from the 16th century, one of which was found to be have a particularly high Sb content (10wt%), but also outliers in leaded red brass, red brass and brass. The leaded red brass refers to an atypical cauldron with decoration on its body (Fig. 7, DDM-C1). There is also a small red brass cauldron, but its dating is uncertain (Fig. 7, PBA-C20). The atypical composition of the two brass cauldrons, from the 16th century, is probably due to their late dating (SOS-C; RF-C12). One of them has a rim that differs from its counterparts from earlier centuries (Fig. 7; SOS-C). Although not unequivocal, this strong relationship between leaded bronze and cauldrons is recurrent in Late Medieval Western Europe [16, 48, 49] and [50] for the largest example. It is noteworthy that of the 30 cauldrons analysed in this study (47 analyses), 18 have antimony levels above 1wt%, up to 10wt% in the case of a 16th-century leaded copper cauldron (for all 47 analyses: Sb 1.8wt% avg., 2.3wt% sd). Most have significant arsenic content (for all 47 analyses: As 0.6wt% avg., 0,8wt% sd), between 0.5 and 1wt%, with the last copper-lead cauldron reaching between 3 and 5.5wt%, depending on the part analysed. These Sb-rich cauldrons are similar to those studied in [13] or to a leaded bronze cauldron

Table 1 Typology of objects for the most represented categories

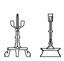
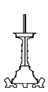
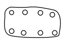
	No. of objects	No. of analyses	Shaping method and scale	Object type	Functional area	Social context of use	Chronology	Production type	Weight range in g
	1	1	Medium-sized casting	Cauldrons	Kitchen	Common ?	12-13th	Mass and serial ?	± 1000–3500
	29	46	Medium-sized casting		Kitchen	Common	14-16th	Mass and serial	
	17	17	Medium sheet—hammering	Skimmers (14), frying pan (1), lid (1) and milk strainer (1)	Kitchen	Common	Late 13-16th	Serial	± 150–500
	2	2	Large sheet—hammering	Kettles	Kitchen or hygiene	Common ?	12-13th	Serial	± 600–6000
	13	13	Large sheet—hammering	Kettles	Kitchen or hygiene	Common	Late 13-16th	Serial	
	4	4	Medium sheet—hammering	Hand basin	Hygiene, table or worship	Privileged	10-13th	Commissioned ?	± 150–1500
	5	5	Medium sheet—hammering	Hand basin	Hygiene or table	Common	14-15th (incl. 15-17th)	Serial	
	8	22	Medium-sized casting	Ewers (7) and jug (1)	Hygiene or table	Common	14-16th	Mass and serial	± 1500–3000
	4	10	Medium-sized casting	Lavabos	Hygiene or table	Less common	14-16th	Possibly commissioned	± 3500–5000
	31	31	Small-sized casting and small sheet—hammering	Spoons	Table	Common	14-16th	Mass and serial	± 10–20
	5	6	Medium-sized casting	Candlesticks and candle holders	Table, rest of the house (or worship)	Privileged	11-13th	Commissioned	± 300–2500
	70	87	Medium-sized casting	Candlesticks and candle holders	Table or rest of the house	Common and less common for weight > 1000 g	14-16th	Mass and serial	± 100–2500
	2	4	Large-sized casting	Candlesticks and candle holders	Worship	Privileged	14-15th	Commissioned	Several dozen kg
	5	6	Medium-sized casting	Statuettes and chest statuettes	Worship	Privileged	12-13th	Commissioned	± 1000–2000
	12	29	Medium-sized casting, excepting 1 mainly obtained by hammering	Statuettes	Worship	Privileged	Late 13-16th	Commissioned	Several dozen kg, excepting hammered one (1.3 kg)
	13	15	Medium-sized casting	Taps	Other equipment	Common	(late 14th) 15-16th	Mass and serial	± 50–100
?	23	23	Sheet—hammering	Undefined vessels (kettle or basin) or repairs	Kitchen, hygiene or table	Undefined	Late 13–16 (incl. 14-17th)	Serial	Undefined

Table 1 (continued)

	No. of objects	No. of analyses	Shaping method and scale	Object type	Functional area	Social context of use	Chronology	Production type	Weight range in g
	2	2	Sheet—hammering	Metal repairs	Kitchen, hygiene or table	Undefined	11-13th	Undefined	Undefined
	27	27	Sheet—hammering	Metal repairs	Kitchen, hygiene or table	Common	Late 13-16th (incl. 15-17th)	Serial	Undefined

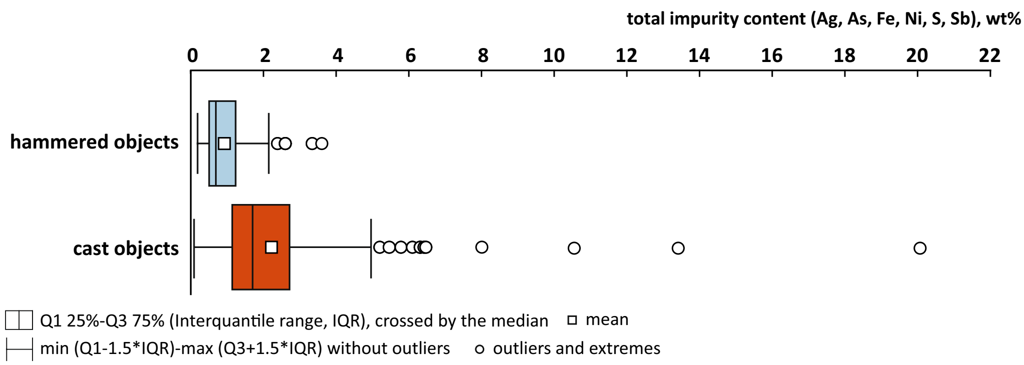


Fig. 4 Contents in wt% of the total impurity content (Ag, As, Fe, Ni, S, Sb) according to the shaping method

from Müsselmow (Germany) with a higher antimony content (9wt%) than tin (2wt%) [51].

Three ewers (MAA-A; POIL-A, AR-A for one foot) belong to the category of leaded bronzes, while six others (DDM-A, MP-A, LC-A, PBA-C21, DSA-A, AR-A for the rest of the vessel) straddle the line between leaded brass and leaded Zn-rich red brass (Zn 7,5-13wt% avg. 10wt%; Pb 8-20wt% avg. 14wt%; Sn 3-6wt% avg. 4wt%; Fig. 7). These compositions are similar to Welsh ewers [15]. In our corpus, three out of eight ewers, all made from a leaded alloy, contain more than 1wt% antimony sometimes up to 5wt% (MAA-A) while for the others, antimony content varies between 0.1 and 0.6wt%. The few indeterminate leaded bronze cast vessel fragments could therefore be ewers or cauldrons, although the incompleteness of the fragments prevents identification. The analysed mortar (PBA-M1) is also made from leaded bronze, as is the case for other mortars dating to the modern period [52]. The lavabos (Fig. 7) also fall into the category of leaded brasses, with varying degrees of lead content depending on the part analysed (Zn 7-18wt% avg. 13.5wt%, Pb 4.5-30wt% avg. 15wt%—excluding one fettling), except for one leaded red brass. The composition of the ewers and lavabos contrasts with that of the aquamanile (12–15th centuries; [53]), which are overall richer in Zn (8-23wt% avg. 15wt%) and lower in lead (0.7-7wt% avg. 2.7wt%).

The candlesticks form an apparently continuous group according to composition, but their chronology and shape allow to distinguish several sub-groups (Figs. 8, 9). Anthropomorphic or zoomorphic candlesticks that date to before the end of the 13th century are brasses or red brasses (Zn 10-19wt% avg. 13wt%; Sn 1,5–6,5wt% avg. 4wt%) with less than 6wt% lead. Small tripod candlesticks, tripod and winged 14th-century examples, tripod spikes, small zoomorphic candlesticks of the 14–16th centuries (spiked candlesticks in the form of a ram or a horse), and part of the branched candlesticks are made from Sn-rich red brass, leaded bronzes (Sn 4-5wt%; Pb 8-24wt%) and Sb-rich leaded coppers (Pb 9-31wt%; Sb 3-5wt%; Sn 2wt%). From the 14th century onwards, most candlesticks have a higher lead content averaging 10.5wt% and up to almost 20wt%. This more significant presence of lead is confirmed in the 15th and 16th centuries when it can reach 31wt% (avg. 15wt%). With the introduction of candlesticks with the high or low bell-shaped bases during the 15th century, most were made of leaded brass or Zn-rich red brass (Zn 7–21.5wt%, avg. 13wt%, Pb 6-28wt% avg. 15wt%), sometimes with a small amount of tin (0–6.5wt%, avg. 2wt%). However, some exceptions exist, such as an atypical candlestick with a very high, bell-shaped foot and an unperforated socket from the Palais des Beaux-Arts de Lille collection (Fig. 8, PBA-C9). Another atypical figural candlestick has

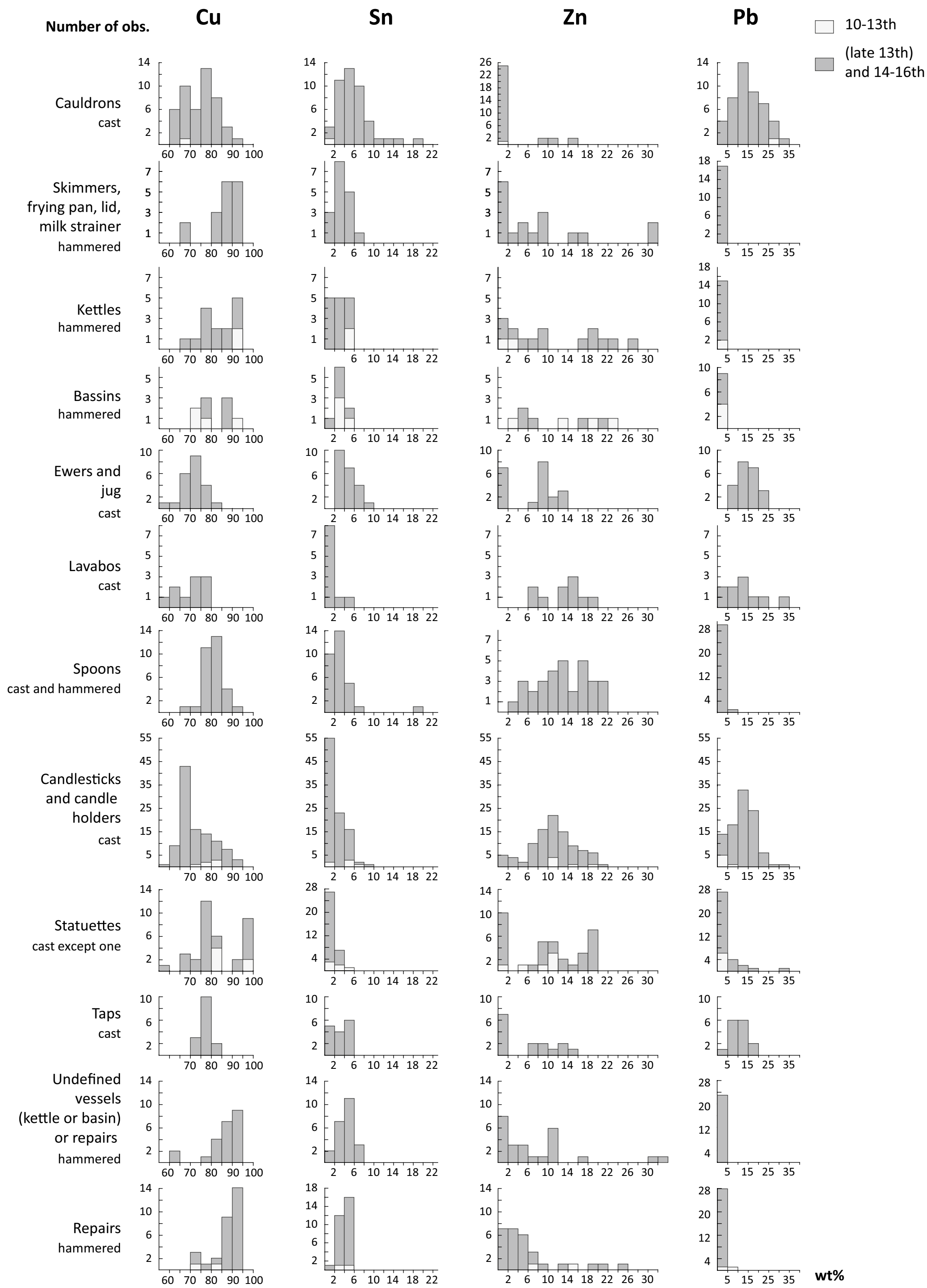


Fig. 5 Distribution in wt% of copper, tin, zinc and lead contents sorted by categories of objects, for the most represented categories

a low-lead brass stem and base, with a figure made of red brass (Fig. 8, PBA-C25). This difference in composition may have been intentional with a play on different colours or could be the result of the later assembly of different parts not originally associated. To conclude, the proportion of brass and lead increase with time together with the introduction of solid of revolution shapes without legs [45]. The altarpieces and monumental candlesticks follow the same trend [54–57]: for instance monumental candlesticks from the Saint-Léonard

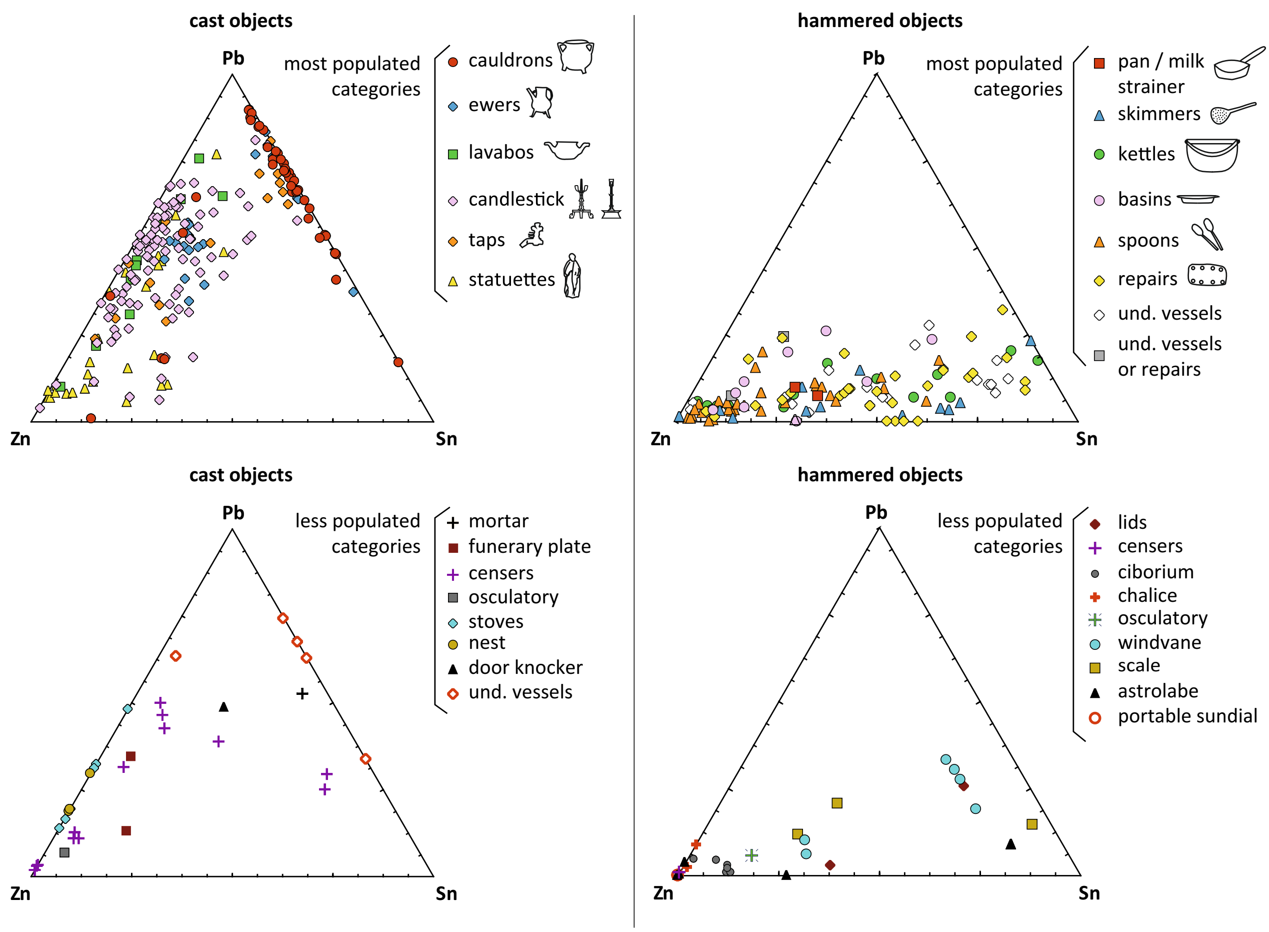


Fig. 6 Ternary diagram plotting the relative contents (in wt%) of tin, zinc and lead, sorted by type of object and by shaping technique, without unalloyed, low-alloyed and leaded coppers ($n = 23$). Please note: as only relative amounts are plotted, superimposed points may not necessarily pertain to the same absolute composition (eg: a 5wt% zinc and lead composition will appear at the same place than a 20wt% Zn and Pb)

church (Léau, Zn 6-33wt%, Pb up to 18wt%), from Saint-Ghislain (Zn 14-17wt%, Pb 9-13wt%) or from Antoing (Zn ± 13wt%, Pb ± 13wt%, Sn ± 3wt%), all dating from the 15th century.

The taps (Fig. 10) also show diverse compositions. They can be made from leaded bronze (Sn 4-6wt%, avg. 5wt%, Pb 10-16wt% avg. 12wt%), leaded brass (Zn 8-16wt%, avg. 12wt%, Pb 5-12wt% avg. 8wt%) or in one case from red brass (Sn 4wt%, Zn 7wt%, Pb 11wt%). Objects from a given site have similar compositions that could be due to preferential supply circuits: different leaded brasses from the 15th century are observed for four taps from the village of Raversijde, while leaded bronzes are found for three specimens from the priory of Villiers-le-Bel. In Caen, however, the same site provides taps with different alloys: one (CC-Ca2) is made of leaded brass while another (CC-Ca1) has different compositions for the moving part and the fixed part (leaded bronze and red brass), that could indicate a replacement.

Two gilded cast statuettes from the 12–13th centuries are made of low alloyed copper (Cu 95-100wt%). A bishop statuette from this period is of low lead red brass. The other more numerous statuettes analysed date from the 15–16th centuries. Most of them are leaded brass (Zn 10-20wt%) with varying levels of lead content (up to 19wt%). The variability of lead content is sometimes significant depending on the different parts analysed. For a statuette (ML-S3), the lead content varies from 3 to 10wt%. In two other cases, the brasses are equally high in zinc (18-19wt%), but lower in lead (2wt%) and there is also a very Pb-rich red brass (Pb 30wt%). The statuette of the 15th-century court jester (MC-PF) from a non-liturgical context is made of a brass that is poorer in zinc (12wt%) than other brass statues and also low in lead (< 2wt%). Although no chronological evolution can be concluded given the small sample size, a prevalence of brass at the end of the period should be noted. If this hypothesis is confirmed by further analysis of other data

Fig. 7 Cauldrons, ewers, lavabos and possible cauldron' legs. Drawings: Nicolas Thomas (LM-C), Joël Eloy (LC-A), Philippe Forré (AR-A), Pascal Saint-Amand (DDM-C1, POIL-A, DDM-A), Lise Saussus (PBA-C18, SOC-C, RF-C2, RF-C4). Photographs: Lise Saussus except for MAA-Pu (C2RMF / Dominique Bagault)

sets, these objects would follow the general trend of most candlesticks, some taps, ewers or lavabos, and other less numerous objects as the door knocker (LC-PDT), the engraved funerary plate, the stoves (such as MAA-RCD1, the upper part of which is a reused candlestick base), and the nest (RF-PG, Fig. 10).

Similarly, while the two 13–14th-centuries censers are made of bronze or brass (as also 12th-century examples in [24]), the two dating from the 14th and 15th centuries are made of leaded brass or leaded red brass (one with a lid of a different composition from its leaded brass foot). From the same period, the osculatory are

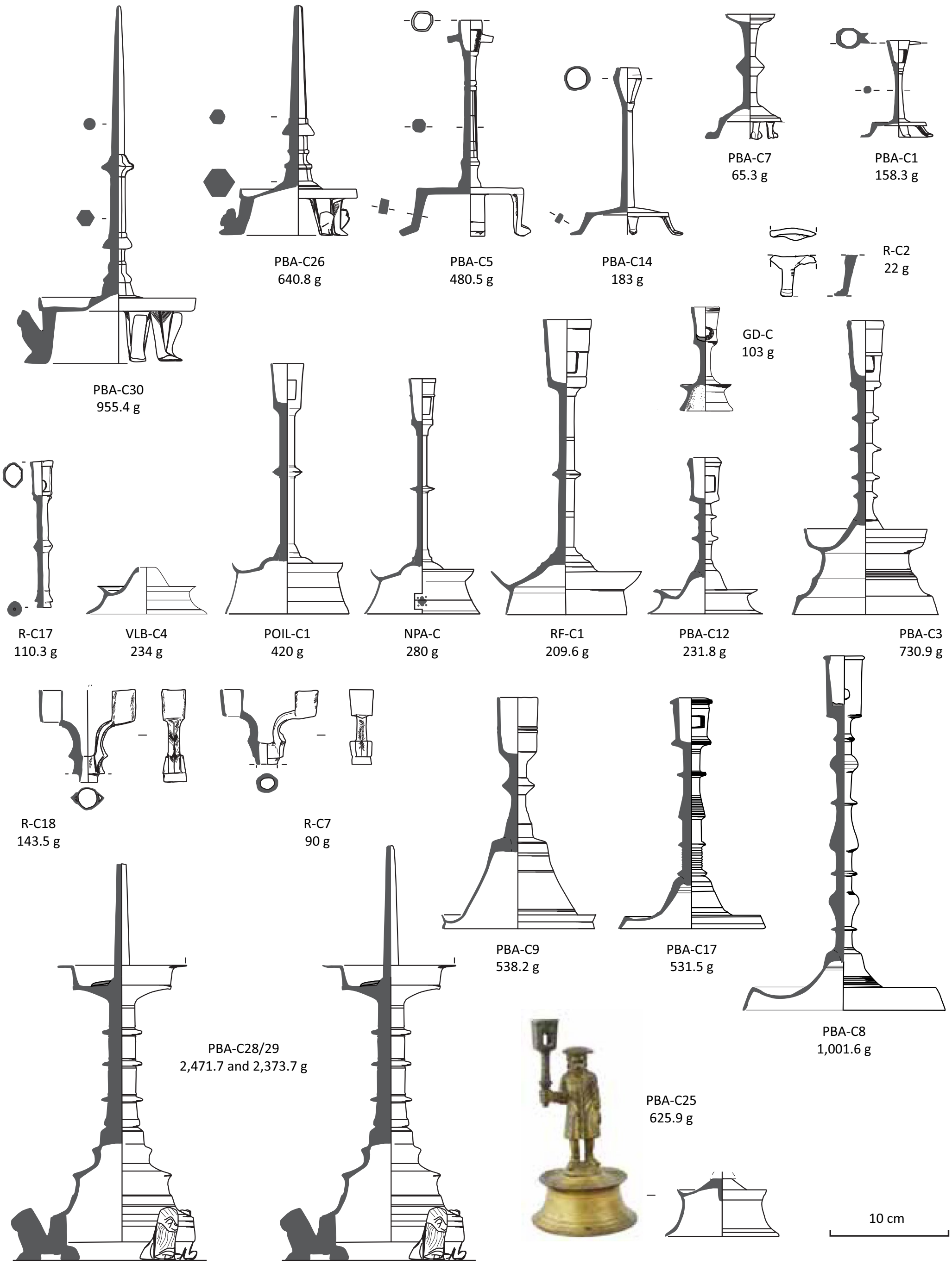


Fig. 8 Candlesticks and candleholders. Drawings: Lise Saussus, except for VLB-C4: Nicolas Thomas. Photographs: Lise Saussus

brass with 18wt% Zn and less than 1.5wt% lead. For the liturgical items, the choice between unalloyed copper and brass seems rather linked to their chronology. Their use of either one had been attributed to the manufacturing techniques by Oddy et al. [24], who observed more hammered low-alloyed coppers and melted brasses. The two hypotheses are not mutually exclusive and should be verified by further analyses of a larger corpus.

To conclude, there are strong links between object type and alloy category for cast items related to the table, kitchen or hygiene. This relationship is further confirmed by a standard one-way ANOVA hypothesis test that enables us to reject the hypothesis that the object type is not

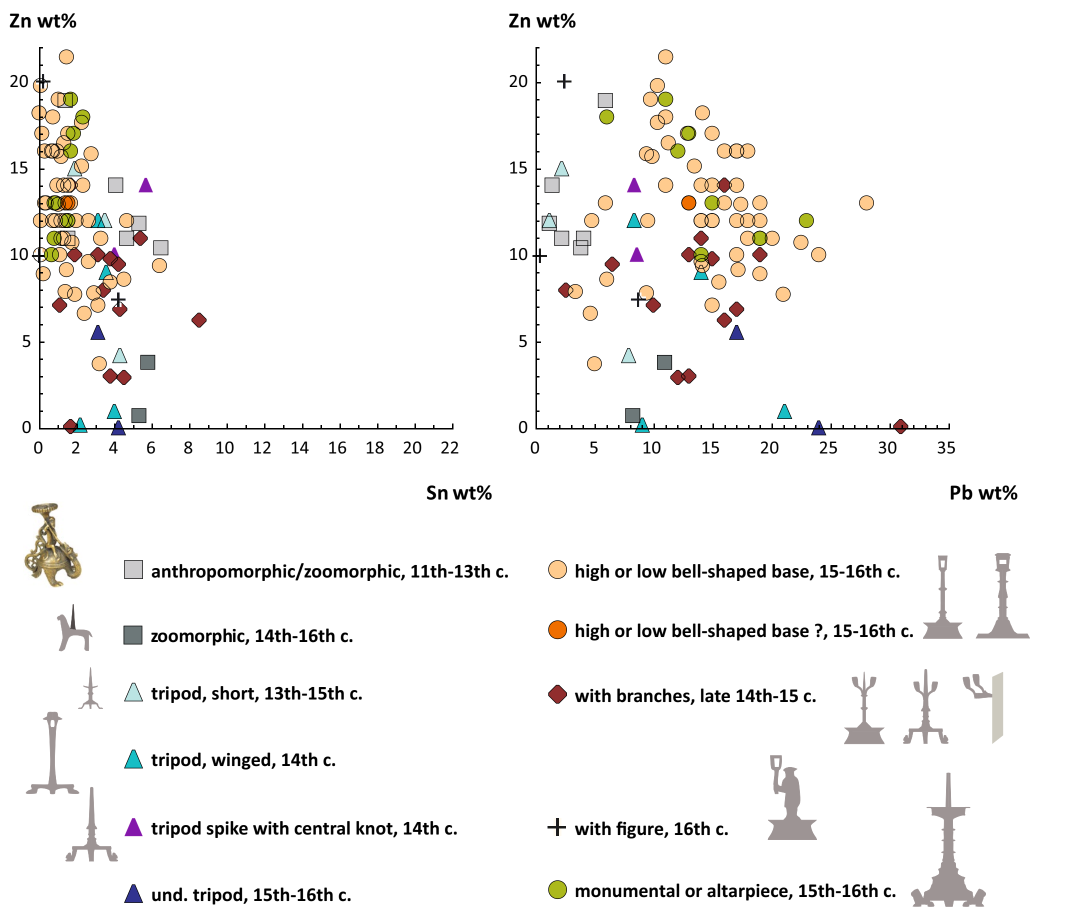


Fig. 9 Binary diagrams plotting the relative contents of zinc/tin and zinc/lead, according to the shape and the chronology of the candlesticks

linked to the zinc, tin and lead content (P value $< 2.10^{-16}$ for each). The liturgical cast items only show distant relationships, if any.

In contrast to most of the cast objects, no particular type of alloy seems to be favoured for hammered objects (Fig. 11). Brass, bronze or red brass can be used for the same type of object. That said, in the case of the bronzes, the distribution of tin has a narrow range, around 5wt% and close to that for red brass. Zinc content for brass and red brass is much more dispersed. The variability of the compositions for hammered items is due to the variability of the zinc content, whatever the category, use, size or date of the object. However, there are a few exceptions, when there is a direct link between alloy composition and object type. Spoons (all dating from the 14–16th centuries), although a relatively dispersed group, are dominated by a higher zinc content. 22 out of 31 spoons are brass (Zn 10-21wt% avg. 16wt%). Five other spoons are made of Zn-rich red brass and three other are made of red brass, whereas one shows a very atypical alloy containing 18wt% of tin, 8wt% of zinc and the highest lead content (5.5wt%) in our set of spoons. Either this spoon is not hammered (due to its tin and lead content), or there is tin and lead enrichment on the surface analysed by PIXE. Despite the limited corpus of brass basins ($n = 4$) and kettles ($n = 6$), it is interesting to note that the zinc-rich kettles appear only at the end of the period (14–16th centuries, for the most part, Zn 17-28wt% avg. 21.5wt%) whereas Zn-rich brass basins are documented from the high Middle Ages onwards: 19wt% zinc for a basin from Nivelles (9–11th centuries), 22wt% for an example from Laakdal (11–12th centuries). Such high zinc content is also observed for basins dating from the same period unearthed in Gotland (Sweden), although other compositions are also reported [46, 58]. At the end of the period, brass is preferably used for producing measuring instruments (alidade of the astrolabe and portable sundial), as seen in the analyses of similar 16th-century astronomical objects in [59]. The hammered liturgical objects, all from the Late Middle Ages, follow the same trends as those observed for cast objects: a statuette of a martyred bishop (Fig. 10, MR-S), most of which is made by hammering, is of a gilded low-alloy copper, a chiselled ciborium (MC-Ci) and the chalice (MC-Ca) are made of gilded brass.

Fig. 10 Taps (CC-Ca2, R-C8-21-22), portable sundial (LC-CS), nest (RF-PG), spoons (BE-Cu1-4-7-12), stove (MAA-RCD1), statuary (MR-S and MC-PF), censer (MC-E5), chalice (MC-Ca), ciborium (MC-Ci), osculatory (MC-P) and door knocker (LC-PDT). Drawings: Lise Saussus, except for CC-Ca2 (Pauline Petit) and MAA-RCD1 (Maggy Destrée). Photographs: C2RMF / Dominique Bagault, except for LC-CS (Lise Saussus), LC-PDT (AWaP / Romain Gilles) and MR-S (C2RMF / Anne Maigret)

The alloy used for the sheet repairs does not necessarily correspond to the original alloy of the vessels.

Results of FAMD and hierarchical clustering

The clustering method (FAMD and hierarchical clustering) reveals five groups of alloys (Fig. 12, Table 2). The first group is made up of kitchen utensils, mainly cauldrons and a few ewers produced from leaded bronze with a high impurity content. The second group consists of tableware, mainly of leaded brass candlesticks. These first two groups are composed of objects that were mass-produced that date after 1300. Group 3 is very similar to Group 2 in terms of alloy composition, but consists of hygiene-related items or stoves, that are either mass-produced or commissioned. The fourth group contains a little more zinc, less lead and less impurities and is represented by commissioned cult objects dating after 1300. Finally, group 5 is mainly constituted of low-lead brass and low-alloyed copper and made up of cult or table objects, dating before 1300.

Discussion

Constrained choices

As alloys that are made or used in a workshop are a mixture of different components, the question prevails as to whether craftsmen freely chose the proportions of the various alloying elements. However, the diagrams and clustering according to object type, functional area, mode of production and chronology show groups for cast objects that are independent of the workshops in which they were made. The hammered objects show a greater variety of compositions for the same type of object, but these are very specific characteristics, with variability affecting only the percentage of zinc. These observations call into question the notion of choice in the interpretation of alloy composition, frequently used in literature, as outlined in the introduction of this paper. Indeed, this raises the question of the craftsmen's degree of independence when using or making an alloy. As a social being, their intentions may be guided by a number of constraints. These may be economic and linked to the

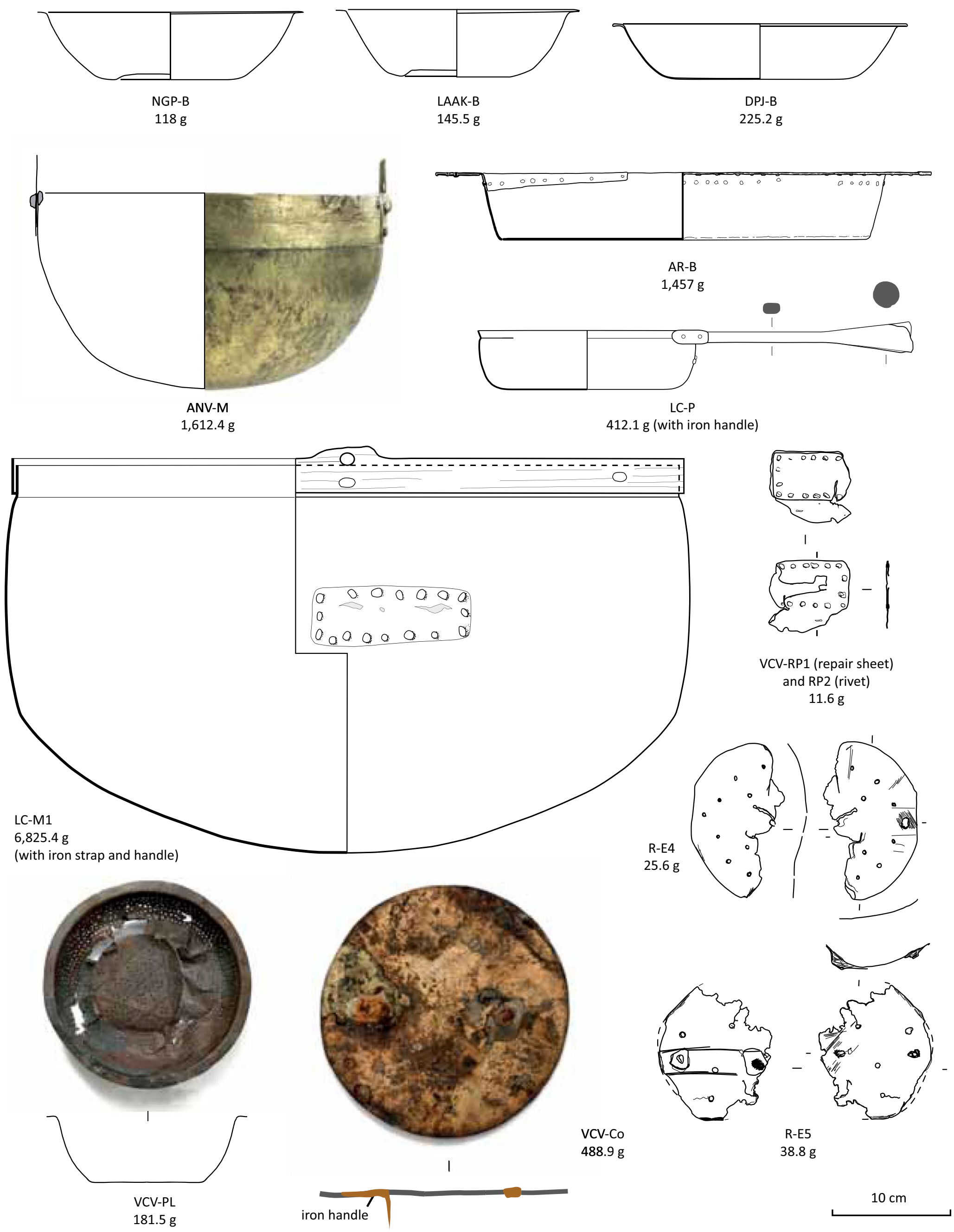


Fig. 11 Hammered objects, including basins, kettles (ANV-M, LC-M1), pan (LC-P), milk-strainer (VCV-PL), lid (VCV-Co), skimmers (R-E4, R-E5), and repair on sheet metal (VCV-RP1). Drawings: Lise Saussus, except LC-P and LC-M1 (Joël Eloy), and AR-B (Philippe Forré). Photographs: Lise Saussus

supply chain of *fresh* metal (from the mine to the merchant, as opposed to *old* metal, i.e. recycled). The supply has an impact on the price of the metal and on the cost of manufacture, according to the objects' weight, their distribution, and their production (serial and mass production, commissioned objects). These factors may vary over time, according to the economic situation. Constraints can also be due to general demand, as the composition of an alloy will change its colour and its mechanical properties. Norms may also govern these choices in the context of regulated markets of the Late Middle Ages that may favour certain alloys or reject others. The constraints are not always related to social issues: they may be linked to the physicochemical properties of the materials

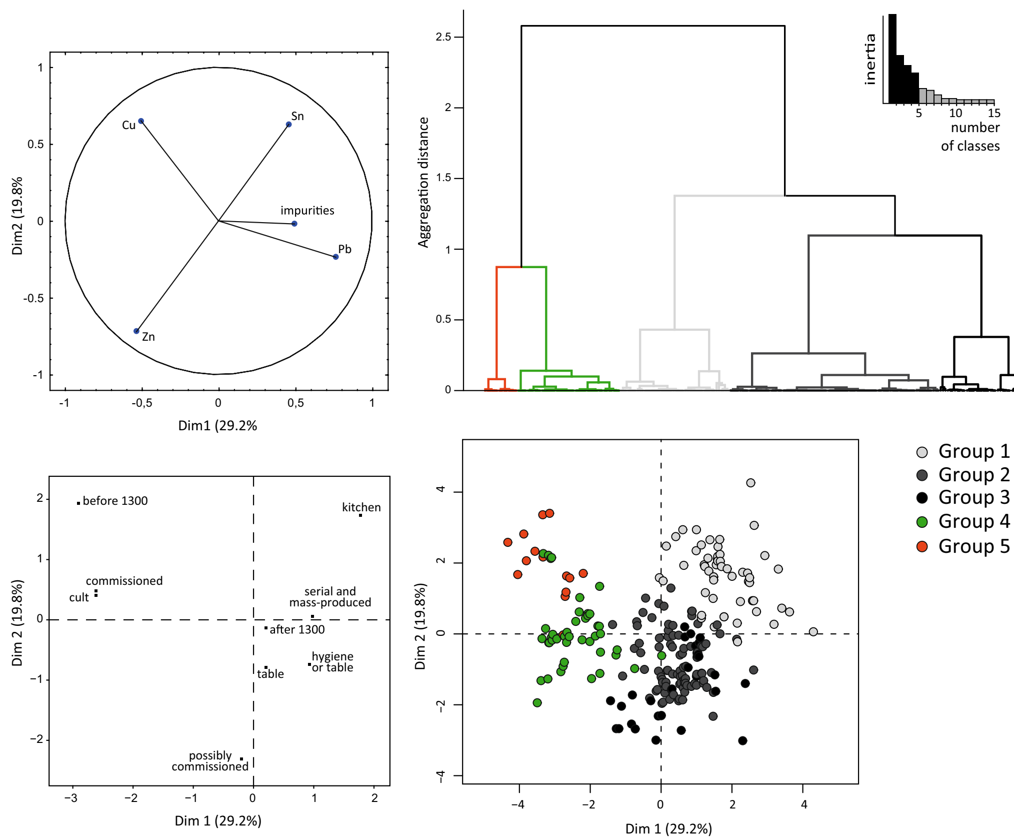


Fig. 12 The five groups obtained by FAMD and hierarchical clustering ($n = 229$ analyses of cast objects). **A** Contributions of the quantitative variables of the FAMD. **B** Contributions of the qualitative variables of the FAMD. **C** Dendrogram of the hierarchical clustering on principal components of FAMD. **D** Graph of individuals of the FAMD

Table 2 Description of the five groups formed by FAMD and hierarchical clustering, n = number of individuals per group

Alloy groups	Description
Group 1 ($n = 53$)	$\bar{x}$ Zn = 0.96wt% / $\bar{x}$ Sn = 5.8wt% $\bar{x}$ Pb = 15.5wt% / $\bar{x}$ sum of impurities = 3.1wt% Almost only kitchen (cauldrons), some ewers Only serial and mass-produced / almost only after 1300
Group 2 ($n = 89$)	$\bar{x}$ Zn = 11.4wt% / $\bar{x}$ Sn = 2.3wt% $\bar{x}$ Pb = 13wt% / $\bar{x}$ sum of impurities = 2.3wt% Almost only table (candlesticks) Only serial and mass-produced / after 1300
Group 3 ($n = 30$)	$\bar{x}$ Zn = 12.8wt% / $\bar{x}$ Sn = 2.3wt% $\bar{x}$ Pb = 12.6wt% / $\bar{x}$ sum of impurities = 2.3wt% Hygiene or table (stoves) Possibly commissioned and serial and mass-produced / after 1300
Groupe 4 ($n = 43$)	Zn = 14.4wt% / $\bar{x}$ Sn = 1.3wt% $\bar{x}$ Pb = 6.7wt% / $\bar{x}$ sum of impurities = 1.4% Commissioned objects related to the cult / after 1300
Groupe 5 ($n = 14$)	$\bar{}$Zn = 9.2wt% / $\bar{x}$ Sn = 3.4wt% $\bar{x}$ Pb = 2.4wt% / $\bar{x}$ sum of impurities = 0.9% Mainly commissioned objects related to the cult and table / before 1300

themselves and their limitations in shaping and use. Several constraints can be expressed simultaneously, that either complement or oppose each other. Once these prerequisites have been established, we will discuss which constraints are expressed within the corpus studied and how strong these constraints were.

The technical constraints related to shaping techniques are strongly expressed in our corpus of hammered objects: craftsmen can not or hardly bypass them. The lead and impurity contents are kept at a low level (Pb < 3wt%, impurities < 1wt%) as they form metallic and non-metallic inclusions that would lead to cracking during the hammering process. For cast objects, one might question whether lead is added to improve the castability of the alloy, i.e. the ability of the metal to properly fill the mould, as demonstrated by [60]. It may indeed be easier to cast thin-walls, such as cauldrons or the bases of domestic candlesticks. For example, the candlestick dating from the second half of the 14th century, from Bouvignes (BOPC-C2), has a thin 1 mm thick wall with 21wt% lead; the same wall thickness is observed for a 15th-century candlestick from Raversijde (R-C8, 19wt% of lead). These reduced thicknesses are not rare at the end of the period although items with thicker walls containing the same lead levels are also observed. However, castability does not seem to be the determining factor for the alloys of this corpus. The craftsman can improve it by increasing the casting temperature of the metal and/or the mould. Lead can also improve the machinability of the alloy, useful for the lathe decoration found on candlesticks. Independant of the shaping technique, lead content is limited when gilding, as it may cause spots on the surface of the metal when a mercury amalgam is used. This problem was observed by Theophilus in his *De Diversis Artibus* (12th century; [61]). As with the statuary and some of the other gilded objects in the corpus, craftsmen favoured low-alloyed coppers, even if others are made of brass. It should also be noted that tin content is kept below 15wt% given that higher tin alloys are difficult to cold-hammer. Equally, the medieval process of brass cementation rarely results in brass above 30wt% zinc, even if experiments have shown that the process could go up to 40wt% and even more under certain conditions [62, 63]. Other technical constraints, such as mechanical properties (elasticity, strength, hardness, etc.) or acoustic quality (for bells) appear to be less significant here.

For cast objects, we have seen that the lead content (that in some cases reaches a third of the total alloy composition) could not be fully explained by the desire to improve the castability of the alloy, this technical constraint could in effect be bypassed. How then can we explain such high levels of lead in cast objects? For a similar object size, cast objects are much heavier than hammered ones, given the fact that their walls are systemically much thicker. Cast items require more metal, from a few hundred grams to a few kilograms. Lead is cheaper than copper and tin, it therefore reduces the cost of the alloy much more significantly for cast objects than for hammered objects (the addition of lead being in any case not possible for the latter due to the technical constraint). From the 13th century onwards, cast objects, in particular cauldrons, were mass-produced, we assume that high lead content are due to a strong economic constraint. The influence of this economic constraint, corollary to a greater demand, contributes to making the produced objects more affordable. This is particularly noticeable for candlesticks from the 14th century onwards. At a time when these were becoming more commonplace in the probate inventories and wills of the working classes [41], the high lead content in brass became almost systematic.

The use of dirty alloys, containing a high level of impurities, must also be questionned. Some alloys with a high lead content (which is not necessarily added during the alloying process, but may be the result of deliberate addition during refining of argentiferous copper) are particularly rich in antimony (Sb $\geq$ 2wt%, $n = 31$) and arsenic ($\geq$ 1wt%, $n = 16$). Most of Sb-rich alloys are cauldrons and ewers (and the mortar) made of leaded bronzes, but also some taps (some rich in As) and a few atypical 14–15th-century candlesticks made of leaded copper or leaded bronze. Dungworth and Nicholas [13] highlighted that, from the 13th century onwards, Sb-rich leaded coppers were most probably a by-product of silver production by liquation of fahlores, as also highlighted for the early modern period, for instance in [64]. The use of a by-product with limited refining also illustrates an economic constraint for cast products: the more refined an alloy is, the more it costs. Leaded alloys with high impurities content are cheaper but quite brittle to use with. This metal may refer to the term *caldarium*, given in technical treatises to a leaded (*Mappae Clavicula*, 9th century) or impure (Agricola, 16th century) copper suitable for casting, with the same etymology of *cauldron* as suggested by [13].

The prevalence of leaded alloys, for example for candlesticks, and of dirty alloys for some leaded bronze objects, in particular for kitchen cauldrons, is linked to other mutations in production, such as the introduction of simpler solid of revolution shapes, the application of the strickling technique, the use of less expensive materials in the casting process (clay model instead of wax) and the optimisation of the how the work was organised [45].

For the objects in this study, the normative constraint is very rarely expressed in regulatory texts. There are a few exceptions in Mechelen (in 1320 and 1466) and

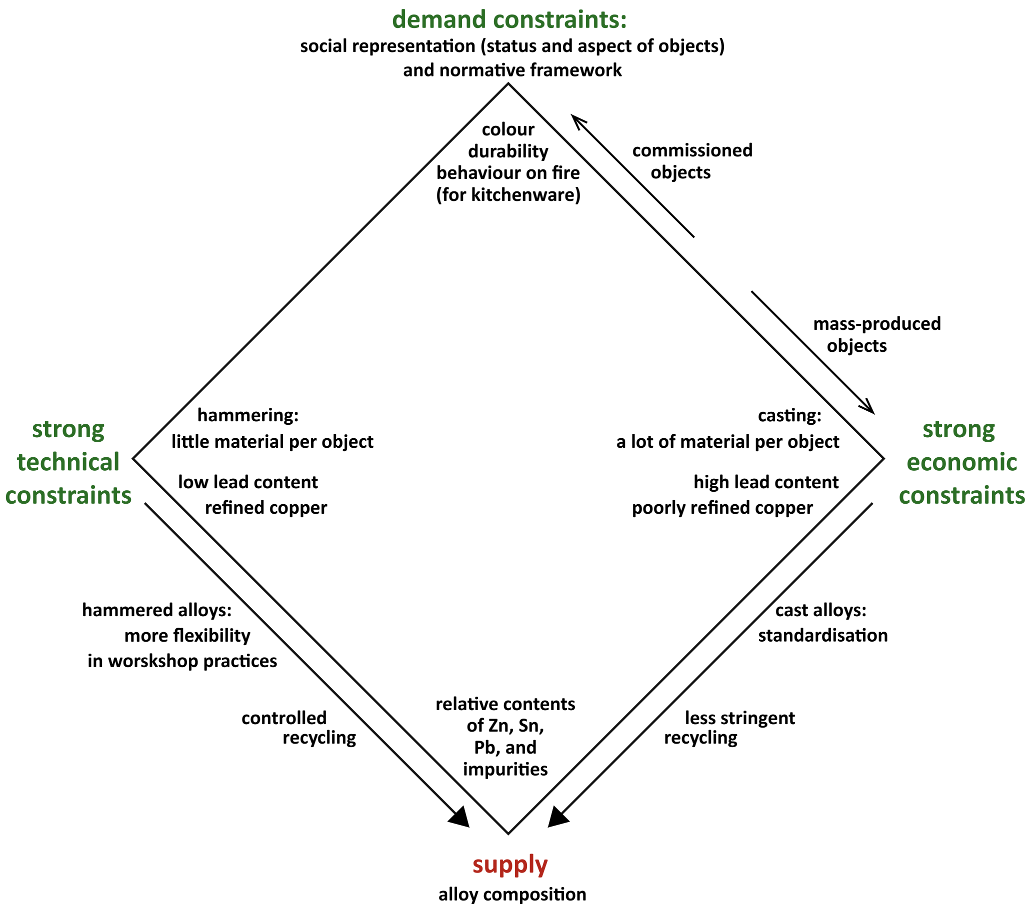


Fig. 13 Overview of the different constraints influencing the composition of the alloys studied

Saint-Omer (in 1325). The regulations for *potghieters* (cauldrons makers) in Mechelen are not very explicit and recommend an alloy made of equal proportions of red copper, white copper and *pottijts*, which is difficult to interpret [65, 66]. The regulation of Saint-Omer is more explicit and rejects, for cauldrons, alloys containing more than 20 pounds of lead for 100 pounds of *metail*, i.e. 16,7% lead [67]. The normative constraint aims to limit lead content, and thus to reduce the influence and circumvention of economic constraint, by guaranteeing the quality of the product, for the consumer and for the reputation of the trade. This can be seen in legal proceedings: in London, for instance, where many pots from the Mosan valley were sold, Aleyn de Sopere complained in 1316 that he bought pots that melted when exposed to fire [68], probably because they contained too much lead. The normative framework, which may have been written as well as orally, does not seem to have had the same constraint everywhere, as for cast objects, these few normative attempts were not really efficient: lead was used in most alloys and at significant levels.

Another constraint, linked to demand, is the social representation of objects. These productions and their materials are receptacles of value for the consumer. Their appearance and their symbolic value can play an ostentatious role. This is particularly the case in liturgy or for tableware. Our results show a clear preference for brass or leaded brass for tableware, such as candlesticks, spoons and also stoves. Brass has a colour close to that of gold, which appears to be highly prized. The same observation can be made for small dress accessories [29, 30]. It is also likely that the golden colour of the tableware, together with the everyday pewter tableware with its silver colour, contributed to an aesthetic of the table aimed at imitating precious metals, and by projection, reproducing the way of life of the wealthier social groups.

To conclude, it appears that the choice of an alloy is expressed in a complex and multifactorial system of constraints that accounts for both material properties, supply and demand (Fig. 13). In this system, some constraints are stronger than others. The technical constraint is more significant for hammered objects and overrides the economic one. Conversely, the economic constraint is the most pronounced for cast objects. In addition, social representations and functional area seem to impact cast objects more strongly, and with preferred alloys by type of object. These correspond to product ranges that will be explored in the following section.

Product ranges

For cast objects, we have seen that there is a strong link between the type of object and the type of alloy. As mentioned before, the type of object is also related to a functional area and to a social context of use. For example, the cauldron used in the kitchen (functional area) is common to many middle class households (social context of use). The relationship between the bulk compositions, object type and the social context of use may lead to distinguish between different product ranges. Brass that contain a high level of zinc and little lead such as unalloyed gilded copper (groups 4 and 5) are mainly found in liturgical or devotional and/or privileged contexts. They may be considered as high-range alloys. Leaded brass objects, typically tableware (candlesticks, spoons) or hygiene-related (lavabos, some ewers), i.e. groups 2 and 3, used in more or less common social contexts form a middle-range group. Finally, kitchen objects, found in most households and represented by leaded bronze cauldrons with a high antimony and arsenic content (group 1) form a low-range category to which table and hygiene objects are rarely associated. To conclude, the more ostentatious the object, according to its social context of use, the higher the zinc content: the more the alloy is perceived as a marker of social status. On the contrary, the more lead, the less the alloy is valued.

These alloy types could also lead to different product ranges, belonging to the same functional area but pertaining to different episods or social levels, especially for objects that hold water for hygiene, namely ewers, lavabos and aquamanilia. Most of the aforementioned aquamanilia [53] contain little lead, and levels of zinc similar to that of some lavabos and ewers, even though the highest zinc contents are found in aquamanilia (up to 23wt%). Conversely, at the other range end, less sophisticated lavabos and some ewers prove to be low-range leaded bronzes, placing them in the same product range as cauldrons. Moreover, regardless of their type, some hygiene items may move from a lower to a higher range depending on whether they are decorated or not. Similarly, a very unusual and ostentatious inscribed 14th-century Welsh jug [15] belongs to the top of the range with a high zinc content (18wt%) and a low lead content (3wt%). However, in some cases, the weight of these objects is so substantial that the economic constraint overrides the ostentatious constraint. Hence, some highly decorated, inscribed and unusually large jugs from the end of the 14th and 15th centuries are made of leaded bronzes or sometimes low-tin alloy [69]. This may be explained by the large quantity of metal required (over 18 kg for the largest jug), the need for more raw material, hence the wish to lower the cost.

For candlesticks dating from the 14th century onwards, the predominance of leaded brass seems to overcome the ranges: comparisons between domestic candlesticks and religious furniture show that devotional or monumental candlesticks follow the same trend. It should be noted that the presence of lead (up to 18wt% for monumental candlesticks) does not seem to alter the golden colour of the brass in any significant way that would impact the ostentatious purpose. However, branch candlesticks probably form a separate group, with less zinc and slightly more tin, but with as much lead (Fig. 9).

The link between alloy type and product range is also related to the type of production (Fig. 13). Commissioned products are most of the time made from high-range alloys, while mass-produced and serial items may be of low- or mid-range alloys. It should be noted that these different types of production, and thus different ranges of alloys, may coexist in the same workshop, as has been demonstrated by the archaeological record [42].

Market standardisation, practices and recycling

Having described the relationship between alloy composition and the objects' status in terms of function and value, we can propose the following hypothesis: around the 14th century, the aforementioned complex system of constraints and the definition of product ranges for copper alloy utensils led to the standardisation of the alloys. This holds for the whole study area and beyond. This is also a corollary of the standardisation of object form (as notably seen by the gradual introduction of simple shapes for candlesticks, cauldrons, ewers and lavabos) and the way of naming things in written records, regardless of linguistic regionalisms [41]. For casting works, these observations strongly suggest that it is illusory to try to distinguish between craftsmen according to the alloys they use. Similarly, alloy compositions cannot lead to determining geographical provenance, not only because of the uniformity of uses but also because different alloys may be cast in the same workshops to produce various ranges of products. Brownsword [70] proposed that tin-rich alloys would be produced in England due to the presence of tin mines on the island whereas zinc-rich alloys would be produced on the continent due to the easy access to zinc ores. Brownsword and Pitt [71, 72] therefore suggested the link between geographical origin and zinc or tin content. Without totally denying the specificities of the metals' market on both sides of the Channel, this hypothesis can no longer be accepted, as bronze utensils were consumed and produced in the Meuse Valley, as shown by the results of the present study and the production waste found in archaeological contexts [45, 73].

This implicit norm for casting shared by different workshops has a margin of tolerance, as the same type of alloys can show a variability in composition. The dispersion within the same type of alloy could be a consequence of both frequent recycling [40], the available means of controlling composition (hammer tests, colours), and, of course, the tolerance that constraints allow.

Conversely, there is no or very little composition uniformity for hammered alloys, except for particular objects such as astronomical instruments. It should be noted that the workshops producing hammered objects are often the same ones that produce cast items, even at different levels of production [45, 74]. In the same workshops, would there therefore be more freedom when producing hammered objects with regard to the market and its constraints? For a Douaisian workshop specialised in hammering, the absence of brass led to the hypothesis of specific workshop practices [31]. These practices, that could also be affected by various constraints, such as supplies, work habits and tradition, need to be confirmed in further work on workshop waste. Another hypothesis would be that, given the fact that these objects require few raw materials and that the objects are produced more by the piece and less in series because of the technical means of hammering without any form of mechanisation, the economic constraints linked to the market have less influence, which tends towards less strong standardised groups of alloys according to object types. A third hypothesis related to recycling can be put forward, without excluding the two previous ones.

There seems therefore to be a paradox: whereas in a system that seems more flexible the compositions of hammered objects are not linked to any type of object, however the technical constraint requires a controlled recycling to avoid introducing too much lead (Fig. 13). In contrast, for cast items for which the economic constraint is the strongest and leads to a standardisation of the alloys, the recycling would be much less stringent as long as the unwanted alloy does not reach significant proportions. For cast objects, the recycling is in any case facilitated by standard products: if the compositions correspond to object type, sorting by object in a workshop is equivalent to sorting by composition. For hammering, recycling may be restricted to sheet metal, to avoid mixing what does not contain lead with what does. Some texts testify to alloy sorting in workshops. In 1482, in the Tournai workshop of the founder Gilles de Grimaumont, there are at least two categories of sorted materials to be recycled: 100 pounds of *mitaille* (scrap) of candlesticks and 300 pounds of other *mitaille* including old basins [75]. Beyond the type of object and alloy category, this grouping distinguishes what is cast from what is hammered. Given the intense recycling, a third hypothesis may be added to explain the lack of uniformity in the alloy composition of hammered objects. The main constraint when recycling to produce hammered items being the low lead content, an undifferentiated recycling of hammered objects may have been carried out whatever the alloys, thus leading to a continuum of compositions ranging from bronzes to brasses (Fig. 3), even if *fresh* metal is introduced into the system.

Conclusion

The analysed alloys and the set of constraints involved in their production show a complex system impacting practices in the workshops of the Late Medieval period. For cast objects at least, this framework of constraints and the close relationship between the composition and the ways in which the objects were produced and consumed tends to show that applying the concept of "choice" or even "strategy" is not an adequate way to approach the problem of alloy composition. This multifactorial system requires a more holistic approach that is not to conceive the object as a material alone but to consider other variables, such as its production and use context, the shaping technique and its chronology. These different variables give meaning to the compositions by identifying different types of alloys. Compositions of cast objects, shared by different workshops, correspond to product ranges that are directly related to the dissemination and consumption of everyday table and kitchenware on a large scale across North-Western Europe. Alloy composition is an element among others that makes it possible to match the production to the market. The composition by object type and according to the social context of use leads to the standardisation of production in the different workshops and markets, leading to a material and cultural horizon that is specific to the end of the Middle Ages.

Our results offer a predictive model for objects in North-Western Europe. If we analyse other cauldrons, or candlesticks, there is a strong probability that they are composed of alloys such as those presented here, even if there will always be outliers. However, other studies are needed extending the same methodology on productions from other areas such as the Mediterranean, Central and Eastern Europe, as well as the Islamic world. This study also suggests the necessity of future work on objects that are still little documented, in particular hammered objects, in order to confirm practices by the study of workshop waste. Identifying deviations from the norm for cast objects and circumventing them should also be considered. Finally, one avenue to explore is the chronological evolution of compositions during the Late Middle Ages and the Early Modern period. There seems to be a preference for brass from the end of 15th century onwards, with this corpus and for other types of production such as pins [76] or from other sites currently being published.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-00915-6.

Additional file 1. Results of elemental composition analyses, according to the analysis technique (PIXE, ICP-AES, SEM-EDS).

Acknowledgements

We are particularly grateful to all the archaeological services and museums for allowing us to access to their collections and for authorising the analyses presented here. We would like to thank Jean Plumier, Catherine Péters and Marie-Laure Van Hove from the Agence wallonne du Patrimoine, Corinne Gardais, Christine Cercy, Carole Deflorenne, François Gentili, David Gucker, Jean-Denis Laffite, Jean-François Nauleau, Xavier Peixoto and Pauline Petit from the Institut national de recherches archéologiques préventives, Étienne Louis and Éric Compagnon of the Service archéologique de Douai (Communauté d'agglomération du Douaisis), Arnaud Tixador and Patrice Korpiun of the Service archéologique de Valenciennes, Leentje Linders, Marnix Pieters, Werner Wouters and Jan Moens of the Agentschap Onroerend Erfgoed, Maarten Berkers of the archaeological service De Zwarte Doos in Ghent, Sofie Scheltjens of the Provinciaal Archeologisch Depot of Provincie Antwerpen, Nicole Meyer-Rodriguez of the Unité d'archéologie de la ville de Saint-Denis, Élisabeth Taburet-Delahaye and Christine Descatoire of the Musée de Cluny—Musée national du Moyen Âge, Laetitia Barragué-Zouita and Sophie Dutheillet de Lamothe of the Palais des Beaux-Arts in Lille, Benoît Wéry of the Musée du Château Fort de Logne, Kathleen Ribbens of the Raversyde Museum, and Philippe Riffaut-Longespé, in charge of the cultural heritage of the city of Troyes. Finally, we would like to thank the Musée départemental des Antiquités de Rouen, the Louvre Museum, the Musée municipal de l'Evéché in Limoges, the Musée intercommunal d'histoire et d'archéologie de Louvres, and the Musée des Arts anciens du Namurois. We would also like to thank the Centre de recherche et de restauration des musées de France (C2RMF) where almost all the analyses were carried out, as well as Nathalie Gondolfo and Jessica Legendre for their help with the ICP-AES analyses. Thanks to all the Aglaé and NewAglaé team, to Claire Pacheco, Quentin Lemasson, Laurent Pichon and Brice Moignard. We are very grateful to Sébastien de Valeriola (Université libre de Bruxelles) for his valuable help and advice in the statistical analysis of the data and the use of R. We also thank Rebecca Peake, James Dodd and Sonja Willems for their proofreading of the English. Finally, we are grateful to the three reviewers for their help in improving the clarity of our paper.

Author contributions

All authors contributed to the material preparation, data collection and study conception. The first draft of the manuscript was written by LS. LS and NT carried out the statistical analysis of the data and the graphic design of the illustrations. All authors have commented on previous versions of the paper. All authors have read and approved the final manuscript.

Funding

The analyses were carried out within the framework of the following funded research projects: *Cuivre, laiton, dinanderie mosane : Ateliers et productions métallurgiques à Dinant et Bouvignes au Moyen Âge (XIII^e^-XVI^e^ siècles)* supported by the Institut national de recherches archéologiques préventives and the Agence wallonne du patrimoine; the PhD project (2013–2017) *La métallurgie du cuivre dans les villes médiévales des Flandres et des environs (XIII^e^-XV^e^ siècles) : hommes, ateliers, techniques et produits. L'exemple de Douai* supported by the F.R.S.-FNRS; the postdoctoral fellowship (from 2019) *From the tomb to the will from 500 to 1500: producters, consumers, techniques, status and diffusion of medieval copper, bronze and brass objects between Meuse and Scheldt* supported by the F.R.S.-FNRS; the project *AllProCop. ALLoys and PROducts: standardization, constraints and choice of compositions in the production of COPper-based alloys in the medieval West* supported by the Iperion program (Integrated Platform for the European Research Infrastructure ON Cultural Heritage) Horizon 2020 (Grant Agreement no. 654028). Finally, this publication was made possible by the support of the DIM-PAMIR network (Domaine d'intérêt majeur – Patrimoines matériels - innovation, expérimentation et résilience) and the Centre de recherche et de restauration des musées de France, by funding the postdoctoral project (2021–2023) *CUIVRAMA. Le cuivre et ses alliages dans les ateliers métallurgiques du Moyen Âge : circulation du métal, cycle de vie des objets et gammes de produits.*

Availability of data and materials

The data tables are provided as additional files. All details can be available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

Received: 15 November 2022 Accepted: 22 March 2023
Published online: 17 April 2023

References

1. Thomas N, Dandridge P. Introduction aux productions en laiton, bronze et autres alliages à base de cuivre dans l'Europe médiévale (12e-16e siècles). Introduction to brass, bronze and other copper-based alloys in medieval Europe (12th–16th centuries). In: Thomas N, Dandridge P, eds. Cuivre, bronzes et laitons médiévaux : Histoire, archéologie et archéométrie des productions en laiton, bronze et autres alliages à base de cuivre dans l'Europe médiévale (12e-16e siècles) / Medieval copper, bronze and brass: History, archaeology and archaeometry of the production of brass, bronze and other copper alloy objects in medieval Europe (12th–16th centuries), [Actes du colloque de Dinant et Namur, 15–17 mai 2014 / Proceedings of the symposium of Dinant and Namur, 15–17 May 2014]. Namur: Agence wallonne du Patrimoine; 2018. p. 17-22. (**Études et documents, Archéologie**).
2. Thomas N, Urban F. Du côté du marché : Uniformité et diversité des productions en alliage à base de cuivre au Moyen Âge. In: Thomas N, Leroy I, Plumier J, eds. L'or des dinandiers : Fondeurs et batteurs mosans au Moyen Âge [Catalogue of the exhibition presented at the Maison du patrimoine médiéval mosan from 28 March to 16 November 2014]. Bouvignes: Maison du patrimoine médiéval mosan; 2014 ; p. 65-76. (**Cahiers de la Maison du patrimoine médiéval mosan**).
3. Egan G, Pritchard F. Dress accessories c. 1150-c. 1450. London: HMSO; 1991. xi-410 p. (**Medieval finds from excavations in London**).
4. Willemsen A, Ernst M. Medieval chic in metal: decorative mounts on belts and purses from the Low Countries 1300–1600. Havertown: David Brown Book Company; 2012. p. 152.
5. Finlay M. Medieval harness pendants. JAMS. 1998;6:25–31.
6. Egan G. The medieval household: daily living c. 1150-c. 1450. London: The Stationery Office; 1998. p. xiii–342 (**Medieval finds from excavations in London**).
7. de Crouy-Chanel E. Le canon : Moyen Âge - Renaissance. Tours: Presses universitaires François-Rabelais; 2020. p. 491.
8. Weinryb I. The bronze object in the Middle Ages. Cambridge: Cambridge University Press; 2016. p. xx–298.
9. Brownsword R. Medieval metalwork: an analytical study of copper-alloy objects. Hist Metall. 2004;38(2):84–105.
10. Heyworth M. Metallurgical analysis of the dress accessories. In: Egan G, Pritchard F, eds. Dress accessories c. 1150–c. 1450. London: HMSO; 1991. p. 387-95. (**Medieval finds from excavations in London**).
11. Bayley J. Alloy nomenclature. In: Egan G, Pritchard F, eds. Dress accessories c. 1150–c. 1450. London: HMSO; 1991. p. 13-7. (Medieval finds from excavations in London).

12. Blades NW. Copper alloys from English archaeological sites 400–1600 AD : An analytical study using ICP-AES [PhD Thesis of Philosophy]. [London]: University of London; 1995.
13. Dungworth D, Nicholas M. Caldarium? An antimony bronze used for medieval and post-medieval cast domestic vessels. Hist Metall. 2004;38(1):24–34.
14. Redknap M, Davis M. Tripod ewers from medieval households: Some thoughts on new discoveries. In: De Groote K, Tys D, Pieters M, eds. Exchanging medieval material culture: Studies on archaeology and history presented to Frans Verhaeghe. Bruxelles: Vlaams Instituut voor het Onroerend Erfgoed; 2010. p. 155-76. (**Relicta Monografieën**).
15. Lewis JM, Brownsword R, Pitt EEH. Medieval *bronze* tripod ewers from Wales. Mediev Archaeol. 1987;31:80–93.
16. Drescher H. Zu den bronzenen Grapen des 12. und 16. Jahrhunderts aus Nordwestdeutschland. In: Aus dem Alltag der mittelalterlichen Stadt [Catalogue of the exhibition held to Bremer Landesmuseum für Kunst- und Kulturgeschichte (Focke-Museum) from 5 December 1982 to 24 April 1983]. Bremen: Sturm Druck; 1982. p. 157-74. (**Hefte des Fockemuseums**).
17. Riederer J. Metallanalysen an Erzugnissen der Visher-Werkstatt. Berliner Beiträge Archäometrie. 1983;8:89–99.
18. Mitchiner MB, Mortimer C, Pollard AM. Nuremberg and its jetons, c. 1475 to 1888: chemical compositions of the alloys. Numis Chron. 1987;147:114–55.
19. Werner O. Analysen mittelalterlicher Bronzen und Messinge I. Archäol Naturwissenschaften. 1977;1:144–220.
20. Werner O. Zusammensetzung neuzeitlicher Nachgüsse und Fälschungen mittel-alterlicher Messinge und Bronzen. Berliner Beiträge Archäometrie. 1980;5:11–35.
21. Werner O. Analysen mittelalterlicher Bronzen und Messinge II und III. Archäol Naturwissenschaften. 1981;2:106–70.
22. Werner O. Analysen mittelalterlicher Bronzen und Messinge IV. Berliner Beiträge Archäometrie. 1982;7:35–174.
23. Bottaini C, Martínez SG, Bordalo R, Beltrame M, Mirão J, Rafael L, Schiavon N. Islamic copper-based metal artefacts from the Garb al-Andalus. A multidisciplinary approach on the Alcáçova of Mārtulah (Mértola, South of Portugal). Herit Sci. 2022;10(1):97.
24. Oddy WA, La Niece S, Stratford N. Romanesque Metalwork. London: British Museum; 1986. 24 pl. et 24. (**British Museum Publications**).
25. Thomas N, Péters C, Urban F, Bourgarit D. Archéologie et archéométrie du Bassinia, la fontaine médiévale de Huy (Belgique, province de Liège). In: Thomas N, Dandridge P, eds. Cuivre, bronzes et laitons médiévaux : Histoire, archéologie et archéométrie des productions en laiton, bronze et autres alliages à base de cuivre dans l'Europe médiévale (12e-16e siècles) / Medieval copper, bronze and brass: History, archaeology and archaeometry of the production of brass, bronze and other copper alloy objects in medieval Europe (12th–16th centuries), [Actes du colloque de Dinant et Namur, 15–17 mai 2014 / Proceedings of the symposium of Dinant and Namur, 15–17 May 2014]. Namur: Agence wallonne du Patrimoine; 2018. p. 249-56. (**Études et documents, Archéologie**).
26. Dumargne A.-C. Les chandeliers en bronze, en cuivre et laiton en Europe du XIIIe au XVIIe siècle. Production, diffusion et usages [Thèse de doctorat]. Université Paris-Saclay; 2019.
27. Castelle M, Dillmann P, Vega E, Blanc-Riehl C, Vilain A, Chastang P, Anheim E. Seal the deal: An extensive study of European historical copper-based seal matrices using a multimodal protocol. J Archaeol Sci. 2020;113:1050–61.
28. Żabiński G, Strzyż P, Goryczka T, Aniołek K, Miśta-Jakubowska E. A copper alloy light cannon from Grodno: an example of early firearms from Eastern Europe. Herit Sci. 2021;9(67):1–22.
29. Bourgarit D, Thomas N. Late Medieval copper alloying practices: A view from a Parisian workshop of the 14th century AD. J Archaeol Sci. 2012;39(10):3052–70.
30. Saussus L, Goemaere E, Thomas N, Leduc T, Goovaerts T, Fourny M. Practices, recipes and supply of a late medieval brass foundry: the refractory ceramics and the metals of an early 15th century AD metallurgical workshop in Brussels. J Archaeol Sci Rep. 2022;42: 103358.
31. Saussus L, Thomas N. Les alliages mis en forme : des pratiques d'atelier ? In: Travailler le cuivre à Douai au XIIIe siècle : histoire et archéologie d'un atelier de proximité. Douai, Louvain-la-Neuve: Association Arkeos/Centre de recherches d'archéologie nationale UCLouvain; 2019. p. 153-68. (**Archaeologia Duacensis/Collection d'archéologie Joseph Mertens**).
32. Garenne-Marot L, Mille B. Copper-based metal in the Inland Niger delta: metal and technology at the time of the Empire of Mali. In: Metals and Mines Studies in Archaeometallurgy Selected papers from the conference Metallurgy *A touchstone for cross-cultural interaction* held at the British Museum, 28–30 april 2005 dedicated to celebrate the career of Paul Craddock during his 40 years at the British Museum. London: Archetype Publications; 2007. p. 159-69.
33. Gaudenzi Asinelli M, Martinón-Torres M. Copper-alloy use in a Tyrrhenian medieval town: the case of Leopoli-Cencelle (Italy). J Archaeol Sci Rep. 2016;7:597–608.
34. Roxburgh MA, van Os BJH. A comparative compositional study of 7th to 11th-century copper-alloy pins from Sedgeford, England, and Domburg, the Netherlands. Mediev Archaeol. 2018;62(2):304–21.
35. Orfanou V, Collinet A, El Morr Z, Bourgarit D. Archaeometallurgical investigation of metal wares from the medieval Iranian world (10th-15th centuries): the ISLAMETAL project. J Archaeol Sci. 2018;95:16–32.
36. Roxburgh MA, Huisman HDJ, van Os B. The Cross & the Crucible: the production of Carolingian disc brooches as objects of religious exchange? Medieval Modern Matt. 2016;5:117–32.
37. Roxburgh MA, Heeren S, Huisman DJ, Van Os BJH. Non-destructive survey of early roman copper-alloy brooches using portable X-ray fluorescence spectrometry. Archaeometry. 2019;61(1):55–69.
38. Bray P, Cuénod A, Gosden C, Hommel P, Liu R, Pollard AM. Form and flow: the 'karmic cycle' of copper. J Archaeol Sci. 2015;56:202–9.
39. Pollard M. Beyond Provenance: New Approaches to Interpreting the Chemistry of Archaeological Copper Alloys. Leuven: Leuven University Press; 2018. 234 p. (Studies in Archaeological Sciences).
40. Thomas N, Saussus L. Cycle de l'objet, recyclage de la matière : Réparer, détourner, fondre et refondre le cuivre et ses alliages (Ve-XVIIIe siècle). In: Henigfeld Y, Husi P, Ravoire F, eds. L'objet au Moyen Âge et à l'époque moderne : Fabriquer, échanger, consommer et recycler. Actes du XIe congrès de la Société d'archéologie médiévale, moderne et contemporaine (28–29 mai 2015, Bayeux). Caen: PUC; 2020. p. 355-68. (**Publications du CRAHAM. Série antique et médiévale**).
41. Saussus L. La métallurgie du cuivre dans les villes médiévales des Flandres et des environs (XIIIe-XVe siècles) : hommes, ateliers, techniques et produits. L'exemple de Douai [Thèse de doctorat]. [Louvain-la-Neuve]: Université catholique de Louvain; 2017.
42. Thomas N. Les ateliers urbains de travail du cuivre et de ses alliages au bas Moyen Âge : archéologie et histoire d'un site parisien du XIVe siècle dans la Villeneuve du Temple (1325–1350) [Thèse de doctorat]. [Paris]: Université Paris 1 Panthéon-Sorbonne; 2009.
43. Bourgarit D, Mille B. The elemental analysis of ancient copper-based artefacts by inductively-coupled-plasma atomic-emission spectrometry: an optimized methodology reveals some secrets of the Vix crater. Meas Sci Technol. 2003;14(9):1538–55.
44. R Core Team. R : A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; 2022.
45. Thomas N, Bourgarit D. Les techniques de production des batteurs et fondeurs mosans au Moyen Âge (XIIe-XVIe siècles). In: Thomas N, Leroy I, Plumier J, eds. L'or des dinandiers : Fondeurs et batteurs mosans au Moyen Âge [Catalogue of the exhibition presented at the Maison du patrimoine médiéval mosan from 28 March to 16 November 2014]. Bouvignes: Maison du patrimoine médiéval mosan; 2014. p. 43-63. (**Cahiers de la Maison du patrimoine médiéval mosan**).
46. Müller U. Zwischen Gebrauch und Bedeutung. Studien zur Funktion von Sachkultur am Beispiel mittelalterlichen Handwaschgeschirrs (5./6. bis 15./16. jahrundert). Bonn: Dr. Rudolf Habelt; 2006. 433 p. (Zeitschrift für Archäologie des Mittelalters).
47. Cameron HK. Technical aspects of medieval monumental brasses. Archaeol J. 1974;131:215–37.
48. Brownsword R. Metal terminology. JAMS. 1990;1:8–11.
49. McDonnell G, Dungworth D. Metalworking evidence. In: Excavations at Launceston Castle, Cornwall. Leeds: Society for Medieval Archaeology; 2006. p. 417-9. (**The Society for Medieval Archaeology, Monograph series**).
50. Butler R, Brownsword R. A mighty crock. JAMS. 1996;4:23–5.
51. Auler J, Hupka D. …*Ehrn Häfen auff dreyen beyn*. Ein gut erhaltener Bronzegrapen mit Gießerzeichen aus dem Landkreis

Ludwigslust-Parchim. Die Kunde Zeitschrift für niedersächsische Archäologie. 2012;(63):111-22.
52. Motture P. Bells & mortars and related utensils: Catalogue of Italian bronzes in the Victoria and Albert Museum. London: Victoria and Albert museum; 2001. p. 240.
53. Barnet P, Dandridge P, eds. Lions, dragons & other beasts: Aquamanilia of the Middle Ages, vessels for church and table. New Haven: Yale University Press; 2006. xi-205 p.
54. De Ruette M, Dupas M, Genin G, Maes L, Vandevivere I. Étude technologique des dinanderies coulées, 1. Le chandelier pascal de Saint Ghislain. Bulletin des Musées royaux d'art et d'histoire. 1984;55(1):25–54.
55. De Ruette M, Dupas M, Genin G, Maes L, Vandevivere I. Étude technologique des dinanderies coulées [suite]. Bulletin des Musées royaux d'art et d'histoire. 1987;58(1):5–42.
56. De Ruette M, Dupas M, Genin G, Maes L, Masschelein-Kleiner L, Vandevivere I. Étude technologique des dinanderies coulées. L'œuvre de Guillaume Lefèvre (synthèse). Bulletin de l'Institut royal du patrimoine artistique. 1988;22:104–60.
57. De Ruette M, Dewanckel G, Dupas M, Duverger E, Maes L, Monfort X, Urban F, Wouters H. Étude technologique des dinanderies coulées. L'œuvre de Renier van Thienen et la restauration du chandelier pascal de Léau (1483). Bulletin de l'Institut Royal du patrimoine artistique. 1993;25:171–209.
58. Trotzig G. Craftsmanship and function: a study of metal vessels found in Viking Age tombs on the island of Gotland, Sweden. Stockholm: Statens historiska museum; 1991. p. 278.
59. Newbury BD. A Non-Destructive Synchrotron X-Ray Study of the Metallurgy and Manufacturing Processes of Eastern and Western Astrolabes in the Adler Planetarium Collection [PhD Thesis of Philosophy]. Lehigh University; 2004.
60. Mille B. D'une amulette en cuivre aux grandes statues de bronze. Évolution des techniques de fonte à la cire perdue, de l'Indus à la Méditerranée, du 5e millénaire au 5e siècle av. J.-C. [Thèse de doctorat]. [Nanterre, Fribourg]: Université de Nanterre & Université de Fribourg; 2017.
61. Dodwell CR, ed. Theophilus, The various arts, De diversis artibus. Oxford: Clarendon Press; 1961. lxxvii-178.
62. Bourgarit D, Thomas N. Ancient brasses: Misconceptions and new insights. In: Hauptmann A, Modarressi-Tehrani D, eds. Archaeometallurgy in Europe III, Proceedings of the 3rd international conference, 29 June to 1 July 2011, Deutsches Bergbau-Museum. Bochum: Deutsches Bergbau-Museum; 2015. p. 255-61. (**Der Anschnitt**).
63. Thomas N, Bourgarit D. La peine emporte-t-elle le profit ? Économie de la production du laiton par cémentation au Moyen Âge. In: Thomas N, Dandridge P, eds. Cuivre, bronzes et laitons médiévaux : Histoire, archéologie et archéométrie des productions en laiton, bronze et autres alliages à base de cuivre dans l'Europe médiévale (12e-16e siècles) / Medieval copper, bronze and brass: History, archaeology and archaeometry of the production of brass, bronze and other copper alloy objects in medieval Europe (12th–16th centuries), [Actes du colloque de Dinant et Namur, 15–17 mai 2014 / Proceedings of the symposium of Dinant and Namur, 15–17 May 2014]. Namur: Agence wallonne du Patrimoine; 2018. p. 71-88. (**Études et documents, Archéologie**).
64. Hauptmann A, Schneider G, Bartels C. The Shipwreck of « Bom Jesus », AD 1533: Fugger Copper in Namibia. J Afr Archaeol. 2016;14(2):181–207.
65. van Doorslaer G. L'ancienne industrie du cuivre à Malines. I. Organisation corporative et développement industriel. Bulletin du Cercle archéologique littéraire et artistique de Malines. 1910;20:53–113.
66. Saussus L, Thomas N. Normes et pratiques d'ateliers chez les travailleurs des métaux non ferreux entre Seine et Meuse du XIIIe au XVIe siècle. In: Bernardi P, Bourlet C, L'Héritier M, Maitte C, Petrowiste J, eds. Objets et contenus des réglementations de métier (Moyen Âge - Époque moderne). Palermo: New Digital Frontiers; forthcoming. (**Economic history frameworks**).
67. Pagart D'Hermansart JG. Les anciennes communautés d'arts et métiers à Saint-Omer. Annexe : pièces justificatives. Mémoires de la Société des antiquaires de la Morinie. 1881;XVII:5-426.
68. Riley HT. Memorials of London and London life, in the XIIIth, XIVth, and XVth centuries : Being a series of extracts, local, social, and political, from the early archives of the City of London, A.D. 1276–1419. London: Longmans; 1868. lxxviii-706.
69. La Niece S, Campbell M. The Asante, Robinson and Wenlok jugs: casting technology of large medieval bronze jugs. Hist Metall. 2020;53(1):19–30.
70. Brownsword R. Compositional analyses as an aid to determine the origins of late mediaeval eagle-lecterns. JAMS. 1992;38(4):4–10.
71. Brownsword R, Pitt E. British late medieval inscribed bronze jugs: A technical study. JAMS. 1996;4:11–15.
72. Brownsword R. Dinanderie, a new perspective. JAMS. 2003;11:18–20.
73. Thomas N, Saussus L. Catalogue des objets et œuvres exposées : Les restes et déchets liés à la production. In: Thomas N, Leroy I, Plumier J, eds. L'or des dinandiers : Fondeurs et batteurs mosans au Moyen Âge [Catalogue of the exhibition presented at the Maison du patrimoine médiéval mosan from 28 March to 16 November 2014]. Bouvignes: Maison du patrimoine médiéval mosan; 2014. p. 84-102. (**Cahiers de la Maison du patrimoine médiéval mosan**).
74. Saussus L. Travailler le cuivre à Douai au XIIIe siècle : histoire et archéologie d'un atelier de proximité. Douai, Louvain-la-Neuve: Association Arkeos / Centre de recherches d'archéologie nationale UCLouvain; 2019. 277 p. (**Archaeologia Duacensis / Collection d'archéologie Joseph Mertens**).
75. Soil de Moriamé E. Les anciennes industries d'art tournaisiennes à l'exposition de 1911. Annales de la Société historique et archéologique de Tournai. 1912;15:xxxi-391.
76. Caple C. Factors in the production of medieval and post-medieval brass pins. In: Hook DR, Gaimster DRM, eds. Trade and discovery: The scientific study of artefacts from Post-Medieval Europe and beyond. London: British Museum; 1995. p. 221-34. (**British museum occasional paper**).

Publisher's Note