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Late medieval copper alloying practices: a view from a Parisian workshop of the 14th century AD

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ABSTRACT

161 late medieval copper-based day-to-day items have been analysed, mostly consisting of small artefacts such as dress fittings. The items were all recently excavated from a 14th century AD metallurgical workshop located in Paris. Eight well-defined copper alloys have been identified that refer to various constraints, the most important one being economics. According to the model proposed, most of the alloys were obtained by dilution of a fresh brass master alloy by scrap metal containing small amounts of zinc, tin and lead. Pure lead was added separately in relatively large quantities, with a limit of 6 wt% Pb marking the boundary between leaded and unleaded alloys. It has been found that the less the cost of the artefact, the more the fresh brass is diluted. For the medium-size castings such as cast vessels, alloys containing large quantities of lead or alloys rich in antimony were used. Such complex alloying strategy pertains more to a small industrial-like plant organisation rather than to craftsman activity, as further supported by a variety of archaeological and historical evidence.

1. Introduction

Medieval copper metallurgy in Western Europe has long been studied at an analytical level through the sole perspective of museum collections, thus concentrating mostly on ecclesiastical ornaments (Werner, 1982; Oddy et al., 1986; De Ruette, 1996), or specific items such as statuary (Riederer, 1980, 1983, 1985; Laub, 1993; Hachenberg, 2006), aquamaniles, funeral tabs, cannons, bells or monumental castings (Cameron, 1974; Tylecote, 1976; Giot and Monnier, 1978; Forshell, 1984; Drescher, 1992; Bayley et al., 1993; Neri, 2004; Giannichedda et al., 2005; Dandridge, 2006; Bellendorf, 2007). Though very valuable, the information supplied by these analytical studies has only been concerned with a minor part of medieval copper production, while omitting all aspects of the production of day-to-day domestic items. This trend was first reversed in the British Isles in the 1980's when, for the first time, a series of analyses were carried out on recently excavated and well-dated small day-to-day artefacts such as sheet metal, small castings and wire (Brinklow, 1975; White, 1982; Heyworth, 1991; Blades, 1995), although unfortunately most analyses have not yet been published. One shall also mention the large contribution in the 1980's by Coventry University on the analysis of North-West European medium-size castings, such as vessels, candleholders or steelyards from museum and private collections, partly published (Brownsword, 2004), as well as the analysis of a few Saxonian items (Zientek, 1996). In France, we have had to wait for the rescue excavations of 2003 on the site of the Hôtel de Mongelas, located in the centre of Paris (Thomas, 2006, 2009; Thomas et al., 2008). In this particular case, an exceptionally well-preserved bronze workshop was revealed, which had been producing primarily day-to-day items: small objects such as dress accessories, household and furniture fittings (Fig. 1), in addition to larger items such as vessels. This discovery provided the starting point for a large interdisciplinary research project involving archaeologists and historians, as well as several branches of archaeometry including ceramic refractory study and metallurgy (Thomas and Bourgarit, 2006; Katona et al., 2007; Thomas et al., 2008; Thomas, 2009).

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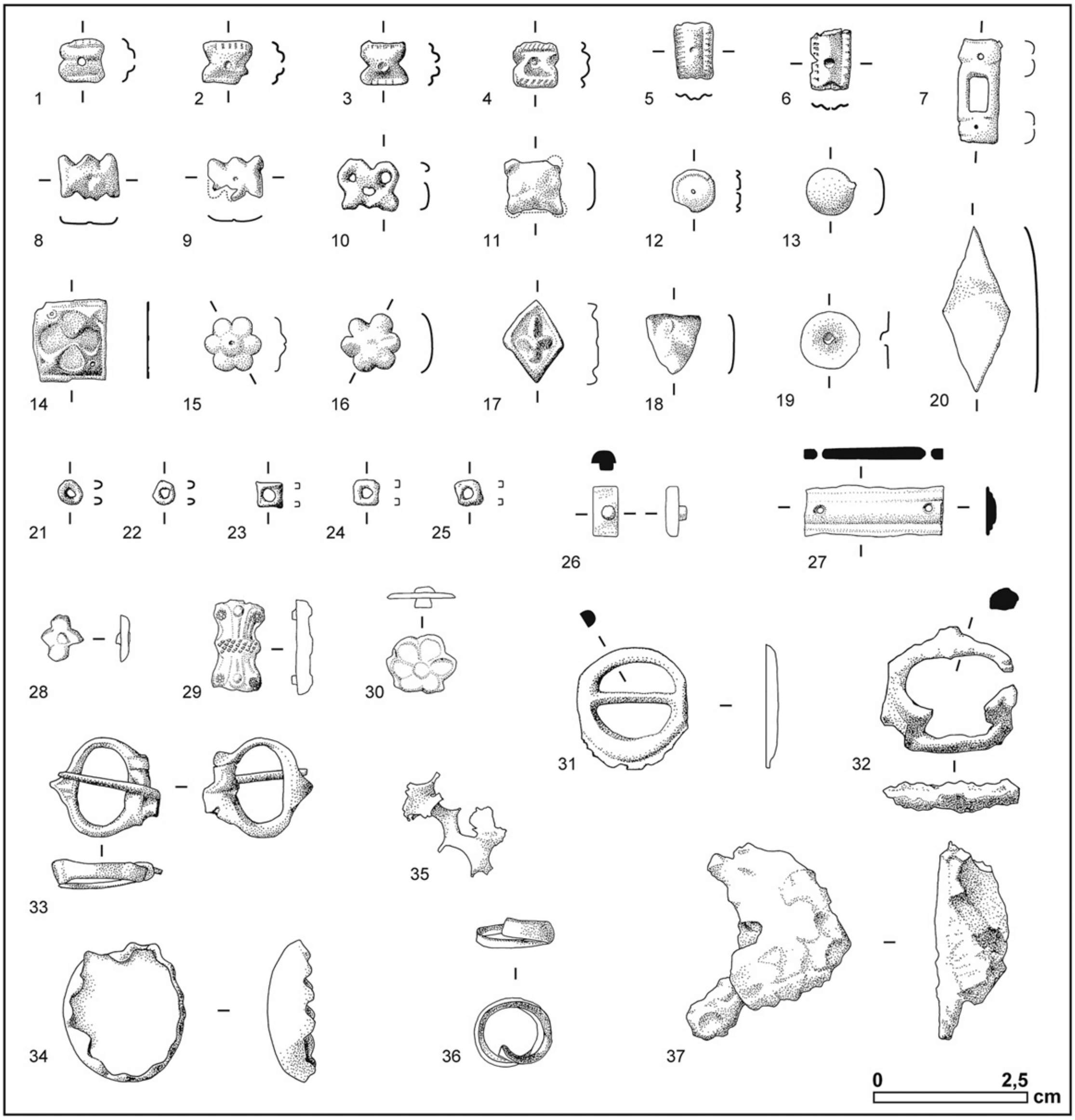

Fig. 1. Selection of copper-based day-to-day items found at the 14th century bronze workshop of Hôtel de Mongelas, Paris. These are mainly dress accessories (#1–25 and 35–36 are sheets, #26–34 are small castings) except #34 (probably a pommel), #35–36 (sheet waste), and #37 (casting waste). Caution, the inventory numbers are specific to this figure and do not correspond to those of the catalogue.

At the site of Hôtel de Mongelas, written records as well as archaeological documentation allow for a precise dating of the metallurgical production between 1325 and 1350. The workshop was located outside of the former inner walls of Paris on a surprisingly large area for this period, the acreage estimated at approximately 750 m^2 (Thomas, 2009: 919–922). As shown by archaeological and historical evidence, the workshop was organised more as a small industrial plant rather than as a craftsman shop (Thomas, 2009: 917–953; Thomas and Bourgarit, 2006; Thomas et al., 2008). Taking the opportunity of such an exceptional archaeological context, elemental analysis of the metal artefacts has been carried out in an attempt to investigate the alloying practices. Two aspects have been focused on. First, the existence of well-defined types of alloys with specific applications has been questioned. Second, the metal supply system within the workshop has been investigated with a particular emphasis on the alloying techniques.

2. Materials and methods

A representative sampling method was undertaken for the elemental analysis, leading to the definition of four main categories, namely small castings, medium-size castings, wire, and sheet metal (Table 1). Small castings and sheet items are mainly dress accessories. Medium-size castings are primarily vessels, see discussion in Section 3.1.These four categories correspond to the three different fabrication methods that have been identified: casting, hammering and wire production.

Due to the small size of a majority of the artefacts and to the difficulty of sampling, surface elemental analysis was carried out by μ-beam Particle Induced X-ray Emission (PIXE) on the AGLAE accelerator facility at the Centre de Recherche et de Restauration des Musées de France (Dran et al., 2000). This method enables large series to be investigated, and is more sensitive than the other technique that was available for this study, that is energy dispersive

Table 1
Overview of the late medieval copper-based day-to-day items analysed for the present study, sorted according to the forming mode. More detailed descriptions are to be found in Table 3.

Small casting				Medium-size casting		Wire		Sheet				
Artefacts		Waste		Waste				Small artefacts		Waste		Total statistics
Total analysed	Kept for statistics	Total analysed	Kept for statistics	Total analysed	Kept for statistics	Total analysed	Kept for statistics	Total analysed	Kept for statistics	Total analysed	Kept for statistics	
22	18	12	10	17	17	14	14	59	58	47	44	161

spectrometry attached to a scanning electron microscope (SEM-EDS). For each sample, the corroded surface layers were removed mechanically over an approximately 2 × 2 mm area in order to allow the beam to reach the metal. A specific protocol for elemental analysis of copper-based alloys was developed including Co filtering, scanning for homogenisation, and RBS quality control. The latter ensures that the corrosion layer has been correctly removed. Analytical performances were checked at the beginning and the end of each run by using bulk metallic certified reference materials. The good agreement with the certified values and the extent of the variations are reported in Table 2. Note in particular that quite a good sensitivity and accuracy can be claimed for arsenic even when relatively large contents of lead are present (see BAM 227). As far as sulphur is concerned, the detection limit drops down to 0.2 wt% for significant amounts of lead (see BAM 227 and BS 938-1).

Eight analyses were discarded from the statistical treatment presented either because they were redundant (metal waste in the furnace), or because the forming technique could not be determined (see Table 3).

3. Results: alloy types

All results are reported in Table 3. Several graphs will be used within the body of the paper in order to highlight the main observations.

3.1. Forming techniques

The three main forming techniques observed at Hôtel de Mongelas, namely casting, hammering, and wire production were used as the first criteria for sorting of the alloy compositions. Among castings, the lead (Pb) distribution points out two different groups (Fig. 2): all small castings contain less than 6 wt% Pb, whereas casting waste shows both low and high Pb contents. Note that all the other artefacts, i.e. sheet and wire, exhibit less than 6 wt% Pb. It is therefore likely that the high-Pb casting waste is from the production of medium-size vessels as seen in other contexts (Blades, 1995; Dungworth and Nicholas, 2004; Thomas et al., 2010), rather than the small dress accessories recovered at the site. Mould fragments of cast domestic vessels have been recovered on-site clearly testifying for such a local production. Therefore, in the following analysis, all casting waste showing less than 6 wt% Pb will be considered as small castings, whereas the other debris will be ranked as medium-size casting. Large castings such as bells and monumental bronzes are clearly not produced at the site.

Within the wires, two groups appear according to the degree of alloying (Fig. 2). As supported by metallographic examinations of some samples (Thomas et al., 2008), the less alloyed wires (more than 89 wt% Cu) have been formed by plastic deformation, whereas the more alloyed artefacts (less than 84 wt% Cu) have been cast. In the following, the heavily-alloyed wire will be treated as small castings.

Finally, four groups of artefacts were considered for statistical analysis, namely small castings, medium-size casting, wire, and sheet. Ten artefacts were further discarded from the analysis due to their unusual composition (Table 3 and Fig. 2), thus leading to the corpus presented in Table 1.

3.2. Alloy types versus forming techniques

The alloy nomenclature defined by Justine Bayley (1991) will be used as a starting point, although the appellation “gunmetal” for copper-zinc-tin alloys appears here as ambiguous or inappropriate since no guns or fire weapons are part of the studied corpus. The modern American appellation of “red brass” will be preferred here to describe copper-zinc-tin alloys (see for example Tyler and Black,

Table 2
Bulk metallic certified reference materials (CRM) used for the PIXE analysis, with corresponding mean and standard deviation composition measured along the three PIXE runs on the accelerator AGLAE between 2005 and 2006 (wt%, values calculated on two to six measurements depending on the CRM). Certified values are indicated in bolded and shaded.

CRM	S	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Ag	Cd	Sn	Sb	Pb	Bi
MBH 17868	**0.03**	**0.07**	**0.02**	**0.030**	**0.04**	**0.040**	**100**	**0.04**	**0.04**		**0.02**	**0.030**	**0.040**	**0.01**	**0.04**	**0.018**
	<0.04	0.067	0.019	0.039	0.038	0.049	98	<0.1	0.044	<0.02	0.018	0.020	0.034	<0.02	0.061	<0.02
		0.003	0.001	0.008	0.004	0.007	2		0.002		0.002	0.004	0.004		0.005	
SUS RC12-10	**0.1**	**0.050**	**0.040**	**0.1**	**0.040**	**0.060**		**0.2**	**0.09**	**0.010**	**0.050**	**0.040**	**0.2**	**0.05**	**0.09**	**0.090**
	0.16	0.036	0.041	0.11	0.061	0.050	99	<0.2	0.09	0.013	0.045	0.031	0.18	0.044	0.11	<0.1
	0.02	0	0.003	0.00	0.002	0	0		0.013	0	0	0.003	0.01	0.005	0.001	
BAM376	**0.01**	**(0.040)**	**0.021**	**0.023**	**0.02**	**0.02**	**99.5**	**0.022**	**0.020**	**0.021**	**0.016**	**0.019**	**0.02**	**0.020**	**0.024**	**0.020**
	<0.04	0.045	0.022	0.027	0.019	<0.04	98	<0.21	<0.02	0.03	0.017	0.020	0.028	<0.02	<0.03	<0.03
		0	0	0.003	0.001		1			0.01	0.002	0	0.001			
BS 938-1	**0.01**			**0.02**		**0.49**	**77**	**0.26**	**(0.004)**		**0**		**7.16**	**0.03**	**14.8**	
	<0.2	<0.009	<0.005	0.026	<0.010	0.52	79	0.24	<0.09	<0.03	<0.006	<0.007	6.7	0.027	12.4	<0.1
				0.004		0.02	1	0.0002					0.3	0.007	0.4	
BAM227	**0.12**			**0.13**		**0.28**	**86**	**3.46**	**0.08**	**0.0028**			**6.01**	**0.16**	**4.12**	**0.0088**
	<0.2	<0.009	<0.003	0.15	<0.01	0.3	86.1	3.4	0.1	<0.02	0.02	<0.004	5.7	0.1	3.6	<0.05
				0.05		0	1	0.1	0		0		0	0	0.4	
NIST1107t				**0.04**		**0.1**	**61**	**37.3**					**1.04**		**0.18**	
	<0.03	<0.007	<0.003	0.042	<0.01	0.10	60	38.6	<0.06	<0.008	<0.004	<0.004	0.90	<0.006	0.17	<0.02
				0.002		0	3	2.5					0.01		0.01	

Table 3

Elemental composition of all late medieval day-to-day metallurgical items and waste analysed stemming from the site of Hôtel de Mongelas as determined by PIXE (wt%, contents normalised to 100%). Accuracy could not be determined the proper way for the technique used here (see Feinberg et al., 2010), one can only deduce from the analysis of the CRM's (see Table 2) That the accuracy spans mainly between 10 and 30%, depending mainly on the element in its concentration. All artefacts are stratigraphically dated to the beginning of the 14th c AD. The catalogue number refers to the PhD work of Nicolas Thomas (2009), the items having not been drawn for the PhD have no catalogue number. Forming technique and alloy type are reported. The items discarded from statistical treatment are indicated. Their removal is due to one of the 4 following reasons: redundancy, low zinc content, low Pb content (for sheets), no clear forming technique. Consequently, no alloy group has been assigned to these items.

Forming technique	Designation	Inv #	Cat #	Cu	Zn	Sn	Pb	S	Mn	Fe	Co	Ni	As	Ag	Sb	Bi	Alloy type	Discarded from statistics
Small casting	Furnace casting waste	F69-1	–	84	10.1	0.7	3.5	0.1	<0.001	0.5	<0.03	0.08	0.4	0.10	0.4	<0.04	Brass	
		F69-2	–	86	10.5	0.5	2.4	<0.09	<0.003	0.4	<0.03	<0.09	<0.3	<0.08	0.3	<0.2	–	Redundant
		F69-3	–	84	10.2	0.7	3.9	0.1	<0.001	0.5	<0.03	0.10	0.4	0.09	0.4	<0.05	–	Redundant
		F69-4	–	84	10.0	0.7	3.6	<0.1	<0.002	0.4	<0.03	0.10	0.4	0.10	0.3	<0.04	–	Redundant
	Casting waste	1061-19	292	98	<0.10	0.03	1.3	<0.03	<0.002	0.0	<0.005	<0.005	0.1	0.03	0.1	<0.02	–	Low Zn
		1061-20	272	82	11.2	3.0	2.4	0.3	0.009	0.4	<0.006	0.05	0.5	0.09	0.3	<0.04	Brass	
		1066-1	293	89	1.5	3.6	4.6	0.8	<0.002	0.4	<0.008	<0.006	0.3	0.09	0.3	<0.07	–	Low Zn
		2040-1	300	76	18.7	2.4	0.7	0.1	<0.002	0.7	<0.02	0.06	0.3	0.06	0.1	<0.03	Brass	
		2040-2	300	79	14.7	3.0	1.7	0.3	<0.003	0.7	<0.009	0.05	0.4	0.06	0.2	<0.04	Brass	
		2068-1	–	75	12.9	4.3	5.9	<0.2	<0.002	0.9	<0.02	0.11	0.4	0.09	0.3	<0.07	Slightly leaded red brass	
		2072-1	283	79	10.3	3.3	5.5	0.4	<0.002	1.0	<0.02	0.10	0.4	0.10	0.3	<0.06	Slightly leaded red brass	
		2072-16	278	87	6.2	3.1	2.5	0.3	<0.002	0.3	<0.010	<0.03	0.5	0.08	0.2	<0.03	Slightly leaded red brass	
		2072-17	277	84	9.6	0.3	5.1	0.3	<0.001	0.3	<0.02	0.09	0.5	0.10	0.3	<0.03	Brass	
		2072-2	282	76	15.5	1.4	5.2	0.2	<0.001	0.4	<0.02	0.09	0.5	0.11	0.3	<0.04	Brass	
		4007-1	–	80	9.4	3.7	4.5	0.4	<0.001	1.5	<0.02	0.11	0.4	0.11	0.3	<0.05	Slightly leaded red brass	
	Small casting	1055-1	239	82	7.3	4.4	5.0	1.7	<0.003	1.3	<0.03	<0.1	0.4	0.08	0.2	<0.07	Slightly leaded red brass	
		1060-5	91	86	1.9	4.2	5.8	<0.1	0.02	0.2	<0.02	<0.03	1.3	0.03	0.4	<0.08	–	Low Zn
		1061-1	95	92	<0.29	4.5	1.8	0.2	<0.001	0.1	<0.008	0.02	0.5	0.07	0.2	<0.05	–	Low Zn
		1061-2	92	83	10.4	2.8	1.7	0.4	<0.001	0.7	<0.006	0.07	0.4	0.13	0.4	<0.03	Brass	
		1061-3	93	78	17.1	0.8	1.6	0.2	<0.001	0.9	<0.02	0.08	0.5	0.07	0.2	<0.02	Brass	
		1061-5	101	78	16.7	3.0	1.2	<0.1	<0.002	0.5	<0.02	0.06	0.3	0.08	0.2	<0.02	Brass	
		1068-1	94	85	8.3	2.9	1.5	0.4	<0.001	0.5	<0.010	0.06	0.5	0.11	0.3	<0.04	Brass	
		1071-2	219	73	20.2	2.5	1.7	0.1	<0.002	1.2	<0.007	0.08	0.5	0.10	0.3	<0.04	Brass	
		1077-1	98	81	12.1	2.9	2.2	0.3	<0.001	0.7	<0.010	0.07	0.4	0.11	0.4	<0.03	Brass	
		1077-2	187	81	6.7	5.9	3.1	0.8	0.006	1.1	<0.008	0.05	0.5	0.12	0.3	<0.02	Slightly leaded red brass	
		1077-3	233	96	<0.02	<0.004	1.2	<0.05	<0.001	0.0	<0.005	0.06	0.5	0.18	0.7	0.28	–	Low Zn
		1100-1	222	98	<0.2	<0.006	1.3	<0.1	<0.002	0.0	<0.005	0.05	<0.03	0.05	0.2	<0.02	–	Low Zn
		1116-4	186	79	8.6	4.5	5.1	0.3	<0.001	1.1	<0.007	0.07	0.4	0.12	0.3	<0.06	Slightly leaded red brass	
		2012-1	184	83	13.1	1.4	1.5	<0.1	<0.002	0.4	<0.009	0.13	0.2	0.08	0.0	<0.04	Brass	
		2072-20	235	84	6.7	3.3	3.9	0.4	<0.002	0.6	<0.01	<0.06	0.5	0.10	0.8	<0.06	Slightly leaded red brass	
		2073-2	183	81	8.5	4.3	3.9	1.0	<0.002	1.0	<0.02	0.07	0.4	0.08	0.2	<0.05	Slightly leaded red brass	
		3005-1	185	83	10.6	3.0	2.2	0.3	<0.002	0.7	<0.03	0.06	0.4	0.12	0.2	<0.04	Brass	
	Wire	1091-6	218	81	8.0	3.9	4.3	0.4	<0.002	1.2	<0.02	0.10	0.4	0.10	0.3	<0.05	Slightly leaded red brass	
		1102-1	220	82	12.0	4.4	0.9	0.4	<0.001	0.4	<0.02	0.07	0.5	0.13	0.2	<0.02	Brass	
		2073-3	–	80	8.3	5.3	4.2	0.4	<0.002	1.0	<0.02	0.07	0.5	0.15	0.3	<0.05	Slightly leaded red brass	
		2073-4	–	84	11.2	1.7	1.8	0.2	<0.002	0.2	<0.008	0.18	0.2	0.11	0.4	<0.04	Brass	
		4011-1	–	76	11.9	2.6	7.6	0.5	<0.001	0.6	<0.010	0.10	0.4	0.09	0.6	<0.07	Slightly leaded red brass	

(*continued on next page*)

Table 3 (*continued*)

Forming technique	Designation	Inv #	Cat #	Cu	Zn	Sn	Pb	S	Mn	Fe	Co	Ni	As	Ag	Sb	Bi	Alloy type	Discarded from statistics
Medium-size casting	Casting waste	1061-18	290	75	11.3	3.4	8.3	<0.3	<0.002	1.1	<0.03	0.09	0.4	0.07	0.2	<0.08	Leaded brass	
		1089-15	285	75	10.5	3.5	8.0	0.4	<0.002	2.4	<0.03	0.09	0.4	0.05	0.2	<0.09	Leaded brass	
		2010-1	297	72	11.4	3.1	12.2	0.6	<0.002	0.9	<0.02	0.08	0.3	0.10	0.3	<0.10	Leaded brass	
		2037-1	284	72	8.3	4.6	13.0	2.2	<0.002	1.2	<0.007	0.06	0.5	0.13	0.3	<0.10	Leaded red brass	
		2069-1	–	77	8.2	4.8	7.8	0.6	<0.002	0.8	<0.02	0.27	0.4	0.12	0.3	<0.08	Leaded red brass	
		2072-10	–	78	7.1	4.6	9.5	0.4	<0.002	0.5	<0.03	0.09	0.3	0.11	0.4	<0.09	Leaded red brass	
		2072-11	–	84	6.5	0.7	6.0	<0.1	<0.003	0.3	<0.009	0.17	0.4	0.17	1.9	<0.07	Leaded red brass	
		2072-12	–	78	6.0	4.3	10.0	0.3	<0.002	0.5	<0.009	0.08	0.4	0.10	0.4	<0.09	Leaded red brass	
		2072-13	–	73	11.0	3.5	10.2	2.6	<0.002	1.0	<0.02	0.07	0.4	0.10	0.5	<0.09	leaded brass	
		2072-14	289	78	12.9	1.2	6.3	0.3	<0.002	0.4	<0.02	0.07	0.6	0.09	0.3	<0.03	Leaded brass	
		2072-15	275	76	11.9	1.5	9.3	1.0	<0.001	0.3	<0.010	0.08	0.6	0.14	0.3	<0.04	Leaded brass	
		2072-18	n.d.	75	1.1	2.8	18.8	<0.3	<0.002	0.1	<0.010	0.05	0.5	0.10	1.2	<0.10	Leaded copper	
		2072-19	n.d.	77	0.6	2.9	17.3	<0.4	<0.002	0.2	<0.007	<0.03	0.5	0.15	1.2	<0.07	Leaded copper	
		2090-1	288	76	8.5	5.1	8.1	<0.09	<0.002	0.7	<0.02	0.09	0.5	0.09	0.4	<0.07	Leaded red brass	
		2090-2	291	77	8.7	4.5	8.5	0.3	<0.002	0.6	<0.02	0.09	0.4	0.09	0.2	<0.07	Leaded red brass	
		4011-1	299	72	1.0	1.8	22.3	0.1	<0.002	0.2	<0.007	0.17	0.4	0.11	1.6	<0.14	leaded copper	
		4015-1	287	79	6.7	3.7	8.4	1.3	<0.001	0.5	<0.02	<0.02	0.4	0.29	1.5	<0.04	Leaded red brass	
Sheet	Cutting waste	1060-2	–	84	10.6	2.9	1.4	0.1	<0.003	0.6	<0.02	0.04	0.4	0.06	0.2	<0.03	Brass	
		1060-4	–	84	10.7	3.0	1.2	0.1	<0.004	0.6	<0.02	<0.03	0.4	0.07	0.2	<0.03	Brass	
		1116-10	–	84	5.7	3.7	4.8	1.0	<0.001	0.4	<0.010	0.05	0.5	0.21	0.5	<0.05	–	High Pb
		1121-3	–	83	1.9	6.4	6.6	1.0	<0.002	0.8	<0.008	<0.010	0.7	0.35	0.5	<0.04	–	High Pb
		2072-4	–	80	6.2	4.6	7.6	1.1	<0.002	0.6	<0.02	0.10	0.4	0.10	0.4	<0.07	–	High Pb
		2072-5	–	81	12.0	2.6	2.3	<0.1	0.006	1.0	<0.02	0.07	0.4	0.07	0.2	<0.04	Brass	
		2072-6	–	84	9.9	3.0	1.6	0.2	0.005	0.2	<0.009	0.08	0.4	0.11	0.3	<0.07	Brass	
		2083-2	–	81	12.9	2.8	2.0	0.3	<0.002	0.7	<0.009	0.07	0.4	0.10	0.3	<0.04	Brass	
		2083-5	–	81	12.3	2.6	2.2	0.4	<0.002	0.6	<0.009	0.07	0.4	0.09	0.3	<0.03	Brass	
		3019-1	–	84	10.1	2.5	2.0	<0.1	<0.002	1.0	<0.010	0.06	0.3	0.11	0.4	<0.04	Brass	
		3019-2	–	85	10.3	2.1	1.2	0.1	<0.002	0.3	<0.009	0.06	0.5	0.10	0.3	<0.010	Brass	
	Mount	1061-17	16	88	3.8	4.2	2.3	0.1	<0.003	0.2	<0.010	0.08	0.3	0.10	0.5	<0.04	Bronze	
		1068-2	88	79	14.5	3.2	1.8	0.7	<0.002	0.2	0.011	0.07	0.3	0.14	0.2	<0.02	Brass	
		1068-3	89	90	3.2	4.1	1.4	0.3	<0.001	0.1	<0.006	0.05	0.3	0.06	0.2	<0.02	Bronze	
		1089-1	84	86	5.8	3.7	2.0	0.5	<0.003	0.1	<0.004	0.06	0.6	0.13	0.4	<0.03	Red brass	
		1089-2	17	86	7.2	2.8	2.0	0.2	<0.002	0.2	<0.006	0.07	0.4	0.13	0.4	0.11	Red brass	
		1089-3	41	91	3.4	2.8	1.8	0.1	<0.001	0.2	<0.004	0.08	0.4	0.11	0.4	<0.02	Bronze	
		1091-1	22	89	6.4	2.6	1.2	<0.1	0.007	0.4	<0.010	0.06	0.4	0.06	0.2	<0.02	Red brass	
		1091-12	82	90	2.9	3.5	1.8	0.2	<0.003	0.2	<0.009	0.07	0.6	0.11	0.4	<0.010	Bronze	
		1091-13	53	88	6.8	2.6	1.9	<0.1	<0.002	0.1	<0.007	0.09	0.5	0.09	0.2	<0.04	Red brass	
		1091-14	55	87	7.6	2.3	2.0	0.1	<0.002	0.2	<0.010	0.06	0.5	0.10	0.3	<0.03	Bronze	
		1091-15	54	82	13.0	1.7	1.7	0.1	<0.002	0.5	<0.007	0.08	0.4	0.06	0.2	<0.03	Brass	
		1091-2	86	88	5.8	2.8	1.9	0.3	<0.003	0.3	<0.02	0.08	0.4	0.11	0.3	<0.02	Red brass	
		1091-20	66	88	4.3	3.8	2.5	0.3	<0.002	0.2	<0.006	<0.006	0.5	0.10	0.2	<0.02	Red brass	
		1091-21	62	88	7.1	2.4	1.8	0.2	0.008	0.2	<0.004	0.07	0.4	0.10	0.6	<0.04	Red brass	
		1091-22	39	91	4.0	2.5	1.7	0.1	<0.001	0.2	<0.006	0.06	0.4	0.10	0.4	<0.02	Red brass	
		1091-23	38	89	5.0	2.6	2.1	0.5	0.008	0.3	<0.02	0.05	0.5	0.11	0.3	<0.05	Red brass	
		1091-24	4	87	5.7	3.6	1.8	0.6	<0.002	0.8	<0.009	<0.03	0.5	0.09	0.3	<0.02	Red brass	
		1091-25	7	88	4.6	3.3	2.8	0.4	<0.002	0.1	<0.004	<0.04	0.5	0.14	0.3	<0.06	Red brass	
		1091-26	3	93	1.8	3.4	1.5	0.2	<0.002	0.2	<0.008	<0.04	0.5	0.05	0.1	<0.02	Bronze	
		1091-27	2	90	4.2	2.5	2.4	0.5	<0.001	0.4	<0.008	<0.03	0.5	0.09	0.2	<0.04	Red brass	
		1091-28	9	90	3.1	3.9	2.3	0.4	<0.003	0.1	<0.004	0.06	0.6	0.11	0.3	<0.03	Bronze	
		1091-29	6	88	6.8	2.5	1.6	0.2	0.008	0.3	<0.010	<0.04	0.5	0.06	0.2	<0.02	Red brass	
		1091-3	85	82	9.9	3.8	1.6	0.6	<0.001	0.3	<0.004	0.05	0.5	0.07	0.2	<0.02	Brass	
		1091-30	46	82	12.3	2.8	1.3	0.1	<0.002	0.8	<0.008	<0.04	0.3	0.07	0.2	<0.02	Brass	
		1091-31	47	84	9.9	3.3	1.7	1.1	<0.001	0.5	<0.010	<0.03	0.4	0.09	0.3	<0.04	Brass	
		1098-1	26	85	8.6	2.7	1.9	0.1	<0.001	0.5	<0.02	0.08	0.4	0.07	0.2	<0.03	Bronze	
		1098-1	15	90	2.5	3.7	1.8	0.3	<0.001	0.3	<0.006	0.07	0.6	0.13	0.3	<0.02	Red brass	
		1098-2	14	84	8.6	3.8	1.6	<0.1	<0.003	0.9	<0.02	0.07	0.4	0.07	0.3	<0.03	Red brass	

	1116-1	34	82	8.2	3.7	3.3	1.1	0.009	0.3	<0.004	0.06	0.4	0.13	0.3	0.12	Red brass	
	1116-2	13	86	6.7	3.5	2.3	0.4	<0.002	0.1	0.01	0.06	0.6	0.07	0.2	<0.04	Red brass	
	1116-3	52	83	5.0	4.9	5.1	1.1	<0.002	0.5	<0.008	0.05	0.5	0.17	0.7	<0.04	–	High Pb
	1116-5	87	85	7.8	2.5	2.8	0.3	<0.003	0.3	<0.006	0.07	0.6	0.10	0.3	<0.03	Red brass	
	2072-9	–	82	12.2	2.6	2.1	0.1	<0.004	0.5	<0.02	0.06	0.4	0.09	0.4	<0.04	Brass	
	2073-1	80	85	8.4	2.7	2.8	<0.1	0.005	0.4	<0.007	0.07	0.5	0.07	0.2	<0.03	Red brass	
Stamped mount	1091-14	126	90	3.1	3.4	2.2	0.2	<0.002	0.1	<0.004	0.07	0.5	0.12	0.3	<0.04	Red brass	
	1091-15	124	90	4.9	3.0	1.5	0.2	<0.001	0.1	<0.02	0.05	0.5	0.07	0.2	<0.02	Red brass	
	1091-16	125	88	5.9	3.4	2.2	0.6	<0.001	0.1	<0.008	<0.03	0.7	0.06	0.2	<0.02	Red brass	
	1091-17	169	92	1.6	4.7	0.8	<0.1	<0.002	0.2	<0.005	0.06	0.2	0.07	0.2	<0.03	Bronze	
	1091-18	170	92	1.0	4.1	1.6	<0.10	<0.002	0.1	<0.009	0.06	0.5	0.06	0.3	<0.03	Bronze	
	1091-19	171	89	5.1	2.7	2.1	0.2	<0.003	0.2	<0.005	0.10	0.4	0.09	0.3	<0.04	Red brass	
	1098-4	122	87	7.0	2.2	2.8	0.1	0.005	0.3	<0.008	0.08	0.5	0.12	0.3	<0.05	Red brass	
	1116-19	131	93	1.5	3.2	1.3	0.1	<0.003	0.1	<0.004	<0.03	0.6	0.06	0.2	<0.03	Bronze	
	1116-20	132	95	0.8	1.6	1.5	0.1	<0.002	0.1	<0.010	0.08	0.5	0.11	0.3	<0.03	Bronze	
	1116-21	130	89	4.6	2.7	2.0	0.1	0.008	0.3	<0.007	0.07	0.5	0.11	0.2	0.1	Red brass	
	1116-22	168	90	5.1	2.9	1.3	0.1	<0.004	0.3	<0.02	<0.03	0.5	0.05	0.2	<0.02	Red brass	
	1116-23	172	90	3.5	3.2	2.0	0.2	<0.002	0.3	<0.02	0.07	0.4	0.10	0.5	<0.03	Bronze	
	1116-24	163	92	1.4	4.7	1.0	0.1	<0.002	0.2	<0.007	0.05	0.2	0.06	0.2	<0.03	Bronze	
Flat mount	1061-10	103	81	13.6	2.4	2.0	0.1	<0.001	0.6	<0.02	0.08	0.4	0.10	0.3	<0.02	Brass	
	1061-12	228	90	2.8	3.4	1.8	0.2	<0.001	0.1	0.014	0.07	0.5	0.10	0.2	<0.05	Bronze	
	1061-13	106	78	15.5	2.8	1.9	0.2	<0.001	1.0	<0.02	0.07	0.4	0.10	0.2	<0.03	Brass	
	1061-6	227	89	6.7	2.3	1.4	<0.1	<0.001	0.1	<0.005	0.08	0.4	0.07	0.2	<0.02	Red brass	
	1061-8	104	80	14.7	2.2	1.3	0.3	<0.002	0.5	<0.02	0.07	0.3	0.11	0.3	<0.03	Brass	
	1061-9	105	80	13.7	2.8	1.9	0.2	<0.002	0.5	<0.02	0.08	0.4	0.10	0.4	<0.02	Brass	
	1098-3	115	82	11.5	3.5	1.2	0.4	<0.002	0.3	<0.007	0.05	0.5	0.05	0.1	<0.03	Brass	
Sheet	1061-16	202	82	12.4	2.7	1.5	0.1	<0.001	0.4	<0.007	0.07	0.4	0.12	0.3	<0.03	Brass	
	1089-4	199	84	10.0	2.9	1.8	<0.1	<0.001	0.4	<0.006	0.07	0.4	0.10	0.3	<0.02	Brass	
	1089-5	200	84	9.6	3.1	2.0	0.1	<0.003	0.4	<0.008	0.07	0.4	0.10	0.3	<0.02	Brass	
	1089-6	198	89	6.8	2.9	1.0	<0.1	<0.003	0.1	0.012	0.06	0.4	0.05	0.2	<0.02	Red brass	
	1116-6	188	80	12.9	3.4	1.6	0.2	<0.002	0.2	0.015	0.06	0.4	0.11	0.2	<0.02	Brass	
Sheet waste	1060-1	–	86	8.6	3.4	1.2	0.4	<0.002	0.6	<0.007	<0.03	0.5	0.07	0.2	<0.03	Red brass	
	1060-3	–	86	8.0	2.9	1.7	0.2	<0.003	1.1	<0.02	0.05	0.4	0.07	0.2	<0.02	Red brass	
	1089-10	–	85	8.7	2.6	2.6	0.2	<0.003	0.3	<0.02	0.06	0.4	0.10	0.4	<0.03	Red brass	
	1089-11	–	90	1.7	5.6	1.5	0.5	<0.002	0.1	<0.005	<0.02	0.6	0.08	0.3	<0.03	Bronze	
	1089-7	–	89	5.7	2.6	1.3	<0.1	<0.001	0.3	<0.005	<0.03	0.5	0.05	0.2	<0.02	Red brass	
	1089-8	–	88	6.9	3.2	1.4	0.1	<0.001	0.1	<0.006	<0.03	0.6	0.05	0.2	<0.03	Red brass	
	1089-9	–	89	6.2	2.9	1.2	0.1	<0.001	0.1	<0.005	0.05	0.6	0.05	0.2	<0.03	Red brass	
	1091-10	–	87	7.7	2.1	2.1	0.3	<0.002	0.2	<0.02	0.08	0.5	0.11	0.3	<0.03	Red brass	
	1091-11	–	92	1.7	3.0	2.0	0.3	<0.003	0.2	<0.006	0.07	0.5	0.09	0.2	<0.02	Bronze	
	1091-7	–	90	3.0	3.1	1.8	0.1	<0.001	0.2	<0.004	0.08	0.4	0.12	0.4	<0.03	Bronze	
	1091-8	–	89	3.9	3.1	2.6	0.3	<0.003	0.2	<0.005	0.08	0.5	0.12	0.4	<0.03	Bronze	
	1091-9	–	91	2.5	3.2	1.9	0.4	<0.001	0.2	<0.005	0.08	0.5	0.20	0.4	<0.03	Bronze	
	1098-5	–	89	2.4	3.6	3.2	0.7	<0.002	0.2	<0.003	0.07	0.5	0.13	0.5	<0.03	Bronze	
	1098-6	–	88	2.9	4.6	2.8	0.7	0.005	0.2	<0.008	0.05	0.6	0.13	0.3	<0.04	Bronze	
	1098-7	–	90	2.7	4.1	2.0	0.6	<0.001	0.4	<0.008	<0.02	0.7	0.04	0.2	<0.02	Bronze	
	1098-8	–	90	2.3	3.5	2.8	0.4	<0.001	0.2	<0.009	0.06	0.5	0.13	0.5	<0.03	Bronze	
	1116-11	–	88	6.2	2.3	1.9	0.2	<0.002	0.3	<0.004	0.06	0.4	0.12	0.3	<0.05	Red brass	
	1116-13	–	92	2.6	3.3	1.3	<0.1	<0.003	0.1	<0.006	0.06	0.5	0.05	0.2	<0.02	Bronze	
	1116-14	–	89	5.4	2.2	2.6	0.5	<0.003	0.3	<0.007	0.06	0.5	0.14	0.3	<0.05	Red brass	
	1116-15	–	87	5.1	4.3	1.7	0.5	<0.002	0.5	<0.006	<0.02	0.6	0.08	0.2	<0.04	Red brass	
	1116-16	–	87	7.6	2.3	2.2	0.1	<0.002	0.2	<0.010	<0.04	0.5	0.09	0.3	<0.02	Red brass	
	1116-17	–	91	2.5	3.5	1.9	0.2	<0.002	0.1	<0.004	0.06	0.6	0.06	0.2	<0.03	Bronze	
	1116-18	–	85	8.5	2.8	2.3	0.5	<0.003	0.3	<0.009	0.06	0.5	0.11	0.3	<0.03	Red brass	
	1116-8	–	90	3.5	3.0	2.4	<0.1	<0.002	0.2	<0.010	0.06	0.5	0.12	0.4	<0.04	Bronze	
	1116-9	–	89	4.5	3.7	2.1	0.3	<0.002	0.1	<0.009	0.05	0.5	0.08	0.2	<0.04	Red brass	
	1121-1	–	86	9.0	2.1	1.9	0.2	<0.001	0.3	<0.02	0.07	0.4	0.09	0.4	<0.03	Red brass	

(*continued on next page*)

Table 3 (*continued*)

Forming technique	Designation	Inv #	Cat #	Cu	Zn	Sn	Pb	S	Mn	Fe	Co	Ni	As	Ag	Sb	Bi	Alloy type	Discarded from statistics
		1121-2	–	86	8.4	2.1	2.1	0.1	<0.002	0.3	<0.02	0.06	0.5	0.10	0.3	<0.04	Red brass	
		1121-4	–	87	7.3	2.7	1.8	0.3	<0.003	0.2	<0.005	0.04	0.6	0.12	0.3	<0.05	Red brass	
		2072-3	–	91	<0.06	5.2	2.8	0.5	<0.001	0.1	<0.009	0.06	0.4	0.11	0.3	<0.06	Bronze	
		2072-7	–	86	8.3	2.8	1.9	0.2	<0.002	0.3	<0.005	0.09	0.5	0.09	0.3	<0.05	Red brass	
		2083-1	–	90	2.6	3.8	2.5	0.6	0.005	0.1	<0.006	0.05	0.6	0.11	0.3	<0.06	Bronze	
		2083-3	–	90	2.5	3.5	2.7	0.6	<0.002	0.1	<0.005	0.06	0.6	0.13	0.3	<0.06	Bronze	
		2083-4	–	91	2.9	3.1	1.6	0.3	<0.002	0.1	<0.010	0.07	0.5	0.10	0.2	<0.02	Bronze	
		3019-3	–	88	6.9	2.7	2.0	<0.1	<0.001	0.1	<0.007	0.06	0.5	0.07	0.2	<0.04	Red brass	
		3019-4	–	88	5.4	4.1	1.8	0.3	<0.002	0.1	<0.004	0.04	0.7	0.11	0.2	<0.05	Red brass	
		3019-5	–	90	4.7	2.7	2.0	0.2	<0.001	0.1	<0.02	<0.03	0.5	0.07	0.2	<0.02	Red brass	
Wire	Wire	1061-11	228	89	3.4	3.0	2.8	<0.1	<0.001	0.1	0.012	0.08	0.5	0.14	0.5	<0.04	Bronze	
		1061-14	260	93	1.5	2.6	1.4	0.1	<0.001	0.3	<0.003	0.06	0.5	0.08	0.3	<0.02	Bronze	
		1061-15	259	94	1.3	2.4	1.0	0.1	<0.002	0.3	<0.009	0.06	0.5	0.07	0.2	<0.03	Copper	
		1061-4	217	95	0.6	1.5	1.4	<0.1	<0.001	0.04	0.01	0.06	0.5	0.07	0.2	<0.02	Copper	
		1061-7	227	90	4.4	2.6	1.9	0.2	0.005	0.3	<0.010	0.08	0.4	0.10	0.4	<0.03	Copper	
		1071-1	231	93	0.7	1.8	2.6	0.1	<0.001	0.3	<0.010	0.08	0.6	0.12	0.3	<0.05	Copper	
		1089-12	263	93	1.1	2.0	2.4	0.4	<0.002	0.5	<0.008	0.06	0.4	0.08	0.4	<0.04	Copper	
		1089-13	264	92	0.9	2.2	3.7	0.6	<0.002	0.1	<0.006	0.05	0.5	0.12	0.4	<0.03	Copper	
		1089-14	265	94	1.3	2.3	1.0	0.1	<0.002	0.3	<0.008	0.04	0.5	0.06	0.2	<0.03	Copper	
		1091-4	256	92	1.7	2.0	2.0	0.2	<0.001	0.3	<0.02	0.08	0.4	0.07	0.3	<0.03	Copper	
		1091-5	229	94	1.0	2.3	1.6	<0.1	<0.002	0.1	0.014	0.05	0.4	0.08	0.2	<0.02	Copper	
		1116-7	188	95	0.7	1.6	1.6	0.3	<0.002	0.1	0.015	0.08	0.5	0.13	0.4	<0.03	Copper	
		2072-8	–	90	2.9	3.3	2.9	0.4	<0.003	0.3	<0.003	0.07	0.5	0.09	0.3	<0.04	Bronze	
		4014-1	–	97	<0.1	0.6	1.5	0.2	<0.004	0.1	<0.004	<0.05	0.5	0.10	0.3	<0.04	Copper	
Miscelleanous	Miscelleanous	1077-4	303	90	4.7	3.2	1.4	0.1	<0.001	0.4	<0.005	0.05	0.4	0.08	0.2	<0.02	–	Forming method not determined
		1082-1	204	81	14.7	1.6	1.6	0.1	<0.001	0.5	<0.02	0.06	0.4	0.08	0.2	<0.02	–	Forming method not determined
		1137-1	216	82	17.2	<0.004	0.8	0.1	<0.005	0.1	<0.004	0.30	0.1	0.03	<0.01	<0.03	–	Forming method not determined
		2010-1	302	86	7.9	2.2	2.3	0.4	<0.002	0.5	<0.006	0.08	0.4	0.09	0.6	<0.04	–	Forming method not determined
		2010-2	301	85	8.4	2.8	2.0	0.2	<0.003	0.4	<0.008	0.08	0.3	0.09	0.6	<0.04	–	Forming method not determined

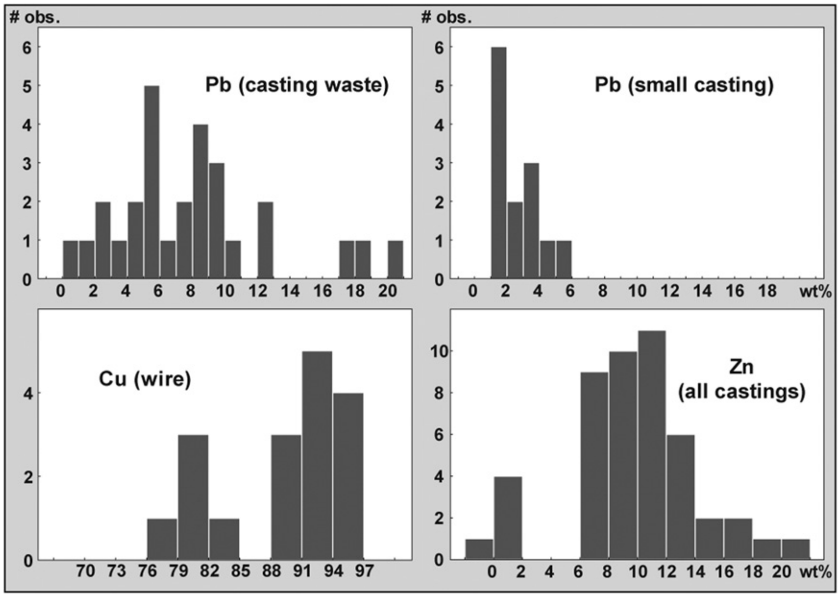

Fig. 2. Distribution of the alloying elements contents within the artefacts of Hôtel de Mongelas (wt%), according to their typological grouping: lead content distribution among the casting waste showing 2 poles with a boundary around 6 wt% Pb, whereas no small casting shows more than 6 wt% Pb; copper content distribution within the wire, showing 2 groups; zinc content distribution within all castings (artefacts and waste), showing the 5 anomalous compositions bearing less than 2 wt% Zn (see Table 3 for more details on these artefacts which have been discarded from subsequent statistical treatment).

1992). The borders defined by Justine Bayley will be slightly adapted to our situation.

In order to find out and to sort the different alloys in use at Hôtel de Mongelas, each of the four groups of artefacts (small castings, medium-size casting, wire, and sheet) has been examined separately. The distribution of the contents of the three alloying elements zinc, tin and lead within each group has been the main statistical tool used to discriminate between the different types of alloys. More details are given in the following paragraphs where each of the four groups of artefacts (small castings, medium-size casting, wire, and sheet) is presented one by one. Eight types of alloys may be thus categorised (Table 4, Figs. 3 and 4). Unalloyed copper is defined here as $Sn < 3$ and $Zn < 2$ wt%. Bronzes encompass all compositions with $Sn > Zn$, thus sometimes leading to quite high amounts of zinc (up to 3 wt%). The distinction between brass and red brass is $Zn = 3\ Sn$. Similarly, an alloy is classified as "slightly leaded" when $3–4 < Pb < 6$ wt%, and as "leaded" when $Pb > 6$ wt%.

Small castings are made of two types of alloys, *brass* and a quaternary alloy Cu–Zn–Sn with some lead, referred to as *slightly-leaded red brass* in the following (Fig. 5). Whereas the overall degree of alloying remains the same, contents in Sn, Zn, Pb are clearly distinct for both types of alloys (Fig. 6). Three types of leaded copper alloys are to be seen within the medium-size castings (Fig. 6): *leaded brass*, *leaded red brass* and *leaded copper*, the latter yielding the highest lead contents of all artefacts from the site (17–22 wt %).

Wires are made of two types of alloys (Fig. 6). Most wire artefacts exhibit a copper purity higher than 89 wt%, referred to as *copper* from now on. Due to their relatively low copper grade and high amounts of Sn, Zn and Pb, five wires may be defined as *bronzes*. The sorting of alloy types for items made of sheet is less straightforward, yet, according to the zinc content one may distinguish between three types (Fig. 7 and Fig. 6). Two types have already been encountered in the other groups, namely *bronze* as for the wires and *brass* as for the small castings. The third type of alloy, *red brass*, is specific to sheet.

3.3. Impurities

The pattern of most impurities detected remains roughly the same whatever the alloy type or the forming technique (Fig. 8). The general scheme may be written as in Equation (1),

$$Ni = Ag < As = Sb \tag{1}$$

Table 4
The 8 types of copper alloys at Hôtel de Mongelas according to the forming technique and use. Mean composition and standard deviation are indicated for each type (wt%), thus showing frequent overlapping as further seen on Fig. 9. A 5-letters coding is set up to report the composition grouping for the 5 elements Sn, Zn, Pb, Fe, S.

Alloy type	Typological group	Samples analysed	Cu	Zn	Zn range	Sn	Sn range	Pb	Pb range	S	S range	Fe	Fe range	Alloy code SnZnPb–SFe
Copper	Wire	11	94 ± 2	1 ± 1	A	2 ± 0.5	A	2 ± 1	A	0.2 ± 0.2	A	0.2 ± 0.1	A	AAA-AA
Leaded copper	Medium-size castings	3	75 ± 3	1	A	2.5 ± 0.5	B	20 ± 2	D	0.1	A	0.1	A	BAD-AA
Bronze	Wire + sheets	3 + 31	90 ± 2	2 ± 1	B	3.5 ± 1	C	2 ± 1	A	0.2 ± 0.2	A	0.2 ± 0.1	A	CBA-AA
Red brass	Sheets	48	87 ± 2	7 ± 1	C	3 ± 0.5	B	2 ± 1	A	0.2 ± 0.2	A	0.2 ± 0.1	A	BCA-AA
Slightly-leaded red brass	Small castings	12	80 ± 3	9 ± 2	C	4 ± 1	C	5 ± 1	B	0.5 ± 0.5	B	1 ± 0.3	B	CCB-BB
Leaded red brass	Medium-size castings	8	78 ± 3	7 ± 1	C	4 ± 1.5	C	9 ± 2	C	0.6 ± 1	B	0.6 ± 0.2	B	CCC-BB
Brass	Small castings + sheets	16 + 23	81 ± 3	12 ± 3	D	2.5 ± 1	B	2 ± 1	A	0.2 ± 0.2	A	0.6 ± 0.2	B	BDA-AB
Leaded brass	Medium-size castings	6	75 ± 3	11 ± 1	D	2.5 ± 1	B	9 ± 2	C	0.6 ± 1	B	1 ± 0.8	B	BDC-BB

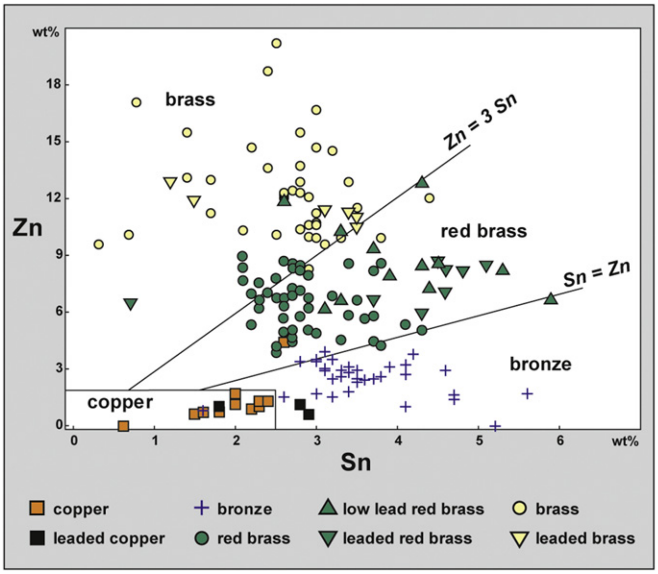

Fig. 3. Sn and Zn contents in all analysed artefacts from Hôtel de Mongelas (wt %), sorted according to the type of alloy. The solid lines mark the boundaries between the different alloy denominations, namely, brass, red brass, bronze and copper.

where most As and Sb contents are around 0.2–0.5 wt% and Ni and Ag around 0.02–0.1 wt%. Three elements show large variations in content: iron, sulphur and antimony.

As far as iron is concerned, two trends may be worth mentioning. First, the highest iron levels are encountered in leaded alloys, although no clear relationship could be observed between iron and lead contents (Fig. 9). Second, there is a weak correlation between Fe and Zn (a linear factor of 0.05 between Fe and Zn with a correlation coefficient of 0.7), as frequently observed for zinc ores (see the discussion and references in Craddock, 1985), although once again the correlation remains poor (Fig. 9). In fact, the iron levels mostly seem to be controlled by the forming technique (Fig. 9); the highest amounts of iron are found in the cast items. Such a trend is less obvious for sulphur, apart for some six cast items which show unusual amounts larger than 1 wt%. One exception is yet to be found for the three items made of leaded copper: although they are cast, they show very low sulphur and iron contents.

Finally, whereas within the whole corpus analysed, antimony contents rarely exceed 0.5 wt%, five items show more than 1 wt% antimony (Figs. 8 and 9). Of note is the fact that the highest antimony contents are encountered in the leaded metals, although there is no positive correlation between Pb and Sb.

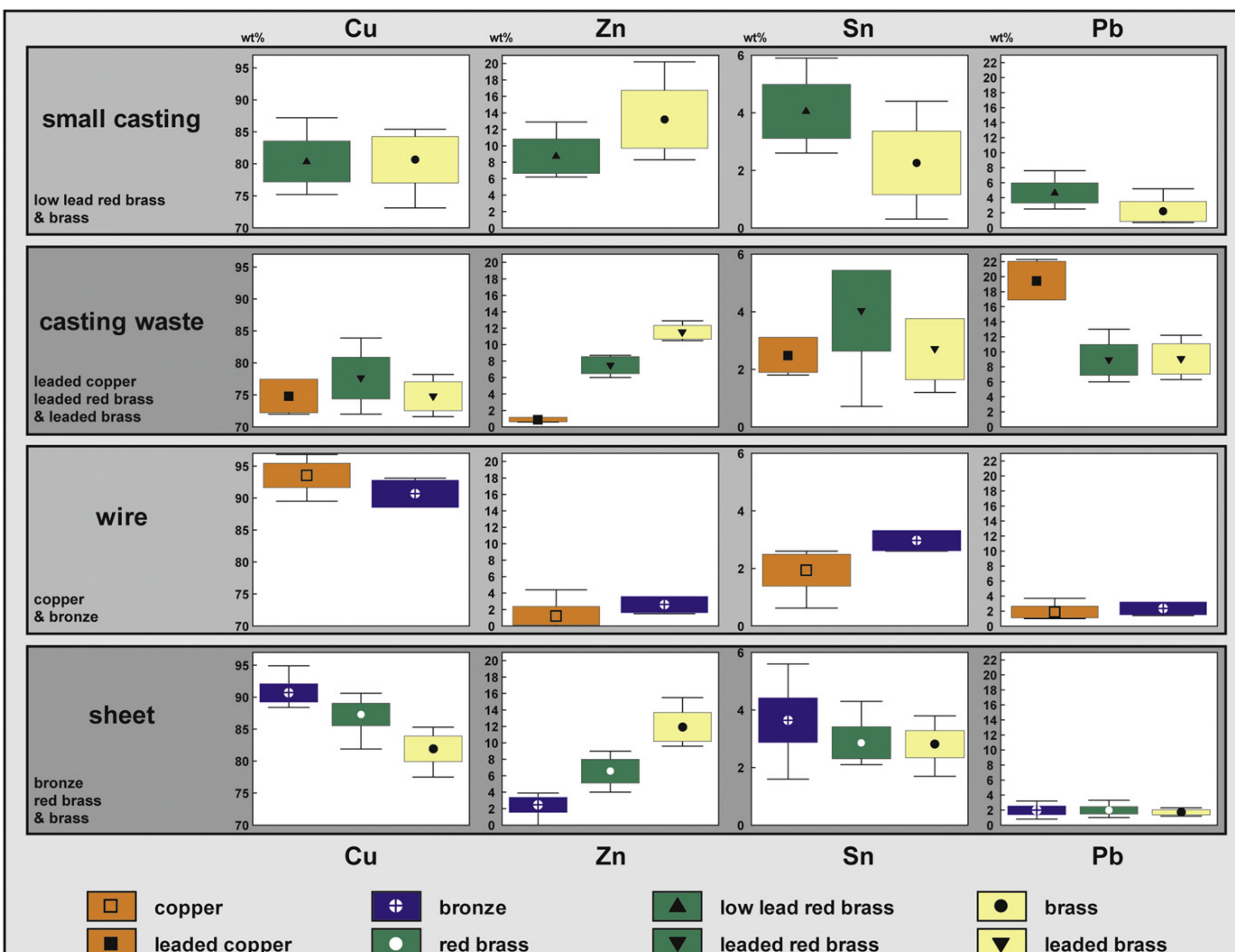

Fig. 4. Whiskers boxes showing the composition in Cu, Zn, Sn and Pb of the 8 different alloy types. The centre of the box reports the mean value, the box edges represent the standard deviation, whereas the whiskers indicate the extrema (wt %).

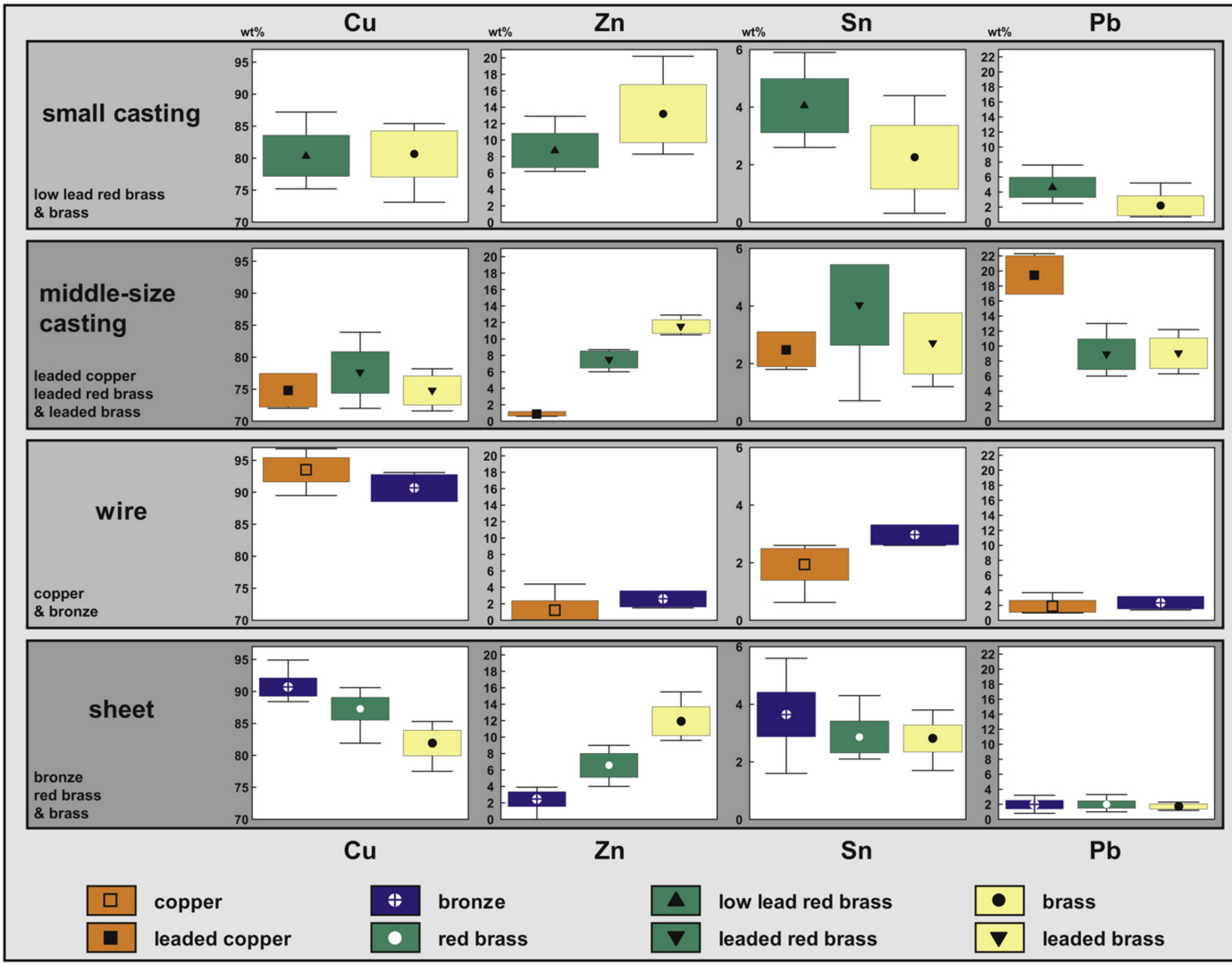

Fig. 5. Ternary diagram plotting the relative amounts (weight ratio) of Sn, Zn and Pb in the small castings. The 2 types of alloys, namely brass (81 ± 3wt% Cu) and red brass (87 ± 2 wt% Cu) are shown, the latter being encircled.

4. Discussion: alloy definitions and specifications

The analysis performed on the metallic artefacts stemming from the Hôtel de Mongelas site led to the identification of eight groups of compositions (Table 4 and Fig. 3). Since these groups are sorted according to their content in the three main elements Sn, Zn and Pb, these eight groups have been referred to as eight types of copper alloys. Different levels of alloying element (Sn, Zn and Pb) and impurity (Fe and S) content have been assigned to each type of alloy. Depending on the chemical element, two, three or even four levels have been observed, each level being labelled by a letter, from "A" to "D" as the content increases. Hence, each of the eight types of alloys has been labelled with a five-letter code.

One may wonder if there is any consistency in the alloy nomenclature defined here. First, the discrepancy of compositions is quite large within one type of alloy (Figs. 3 and 4), leading to an apparent continuum spreading from one type of alloy to the other with frequent overlapping, rather than to a clear separation into composition domains. Second, the eight so-called types of alloys that have come to light actually encompass almost the whole range of copper alloys known in antiquity. Besides, according to Medieval texts and French archives (Tables 5 and 6) the medieval terminology for alloys is far from being precise and similar conclusions may be drawn from English documentary evidences (Lewis et al., 1987; Dungworth and Nicholas, 2004; Bayley, 1991). In fact, it shows that the nomenclature strongly depends on the source, as noted when comparing technical treatises, administrative archives, craft-guild's law or mediaeval encyclopaedic literature. Thus, unfortunately, the historical approach may, alone, not be of much help in our quest to shed any light on well-defined copper alloys.

Yet, several features of our analytical results tend to support the existence of alloy recipes, or at least workshop alloying habits. First, a continuum in alloy compositions does not necessarily reveal an absence of control. In this respect, the comparison with the US modern copper alloy nomenclature may be interesting: for example, the difference between the leaded red brass C83600 (Cu 84–86 wt%, Sn 4–6 wt%, Zn 4–6 wt%, Pb 4–6 wt%) and the leaded tin bronze C92200 (Cu 86–89 wt%, Sn 5.8–6.5 wt%, Zn 3.5–5 wt%, Pb 1–1.8 wt%) is quite tiny (see Table 3 in Schmidt et al., 1992). In stating this, the continuum in our corpus is actually only partial. Hence, while tin and lead contents – and the degree of alloying as represented by the Cu content as well – show a quite continuous pattern indeed, the Zn contents are distributed along well separated poles for each alloy

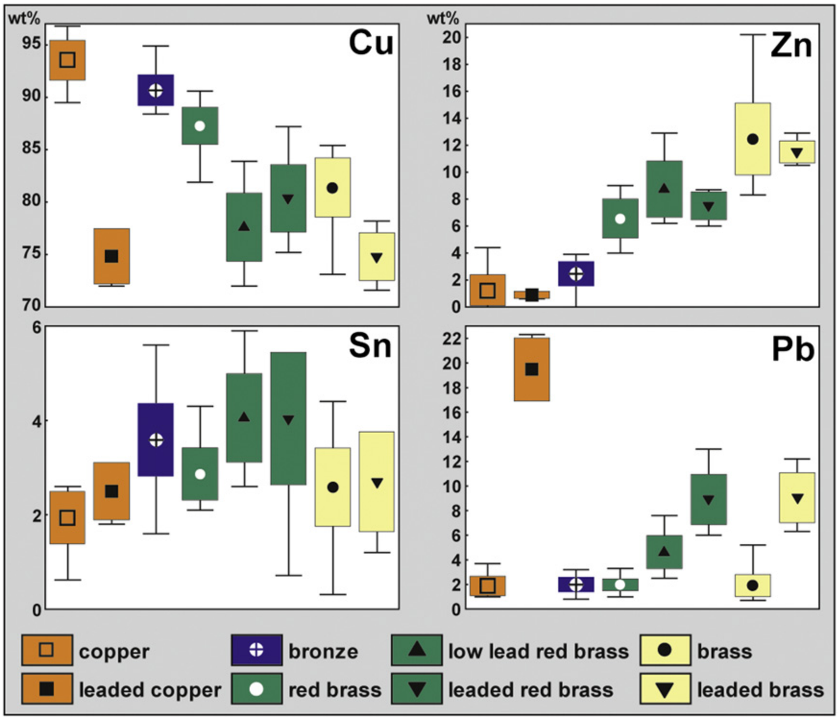

Fig. 6. Box and whiskers plots showing the composition in Cu, Zn, Sn and Pb of the different alloy types, for each group of artefacts of Hôtel de Mongelas: small castings, medium-size castings, wires, sheets. The centre of the box reports the mean value, the box edges represent the standard deviation, whereas the whiskers indicate the extrema (wt %).

type and thus they prove to be very specific to one alloy type (Fig. 10). This means in turn that Zn content is controlling most alloying practice. Note that Sn contents, together with Zn, generate "holes in the continuum" as well. It follows that there is an entire range of Zn/Sn compositions which is not encountered within the corpus analysed, as clearly seen on Fig. 7. This will be further discussed in the Section 5 below.

In addition, whereas the different alloy groups have arisen by considering each forming technique separately, mean values and standard deviation of alloying elements that characterize each type of alloy remain unchanged from one group to the other (Table 4, see also for example the red brass in the small castings and the sheet, Fig. 5).

Finally, the consistency of the present alloy nomenclature may be further supported by the fact that the use of each type of alloy may be related to one or several specific constraints, be they technical and/or economic, or other. This will be discussed in the following.

4.1. Technical constraints

The different metal compositions can be clearly assigned to specific requirements, the first being the forming technique, namely casting versus plastic deformation. In this respect, the two

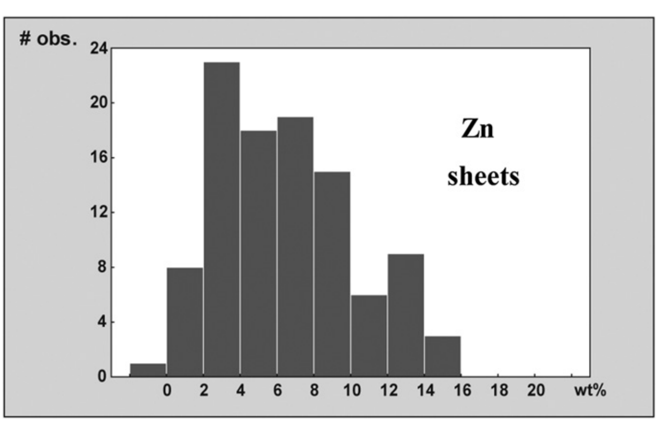

Fig. 7. Zinc content distribution within all sheets of Hôtel de Mongelas (artefacts and waste represent 102 samples), showing the 3 composition poles: around 3 wt% Zn, between 4 and wt 9% Zn, and more than 9 wt% Zn.

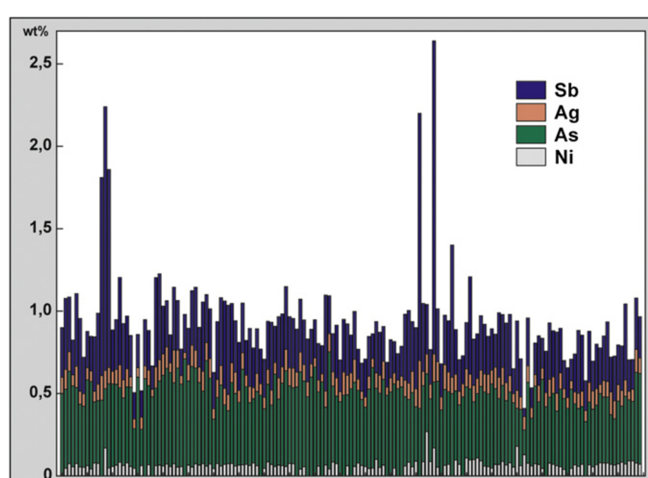

Fig. 8. Main impurities detected in the metal of the 161 analysed artefacts from Hôtel de Mongelas, showing the homogeneity of the pattern (wt %).

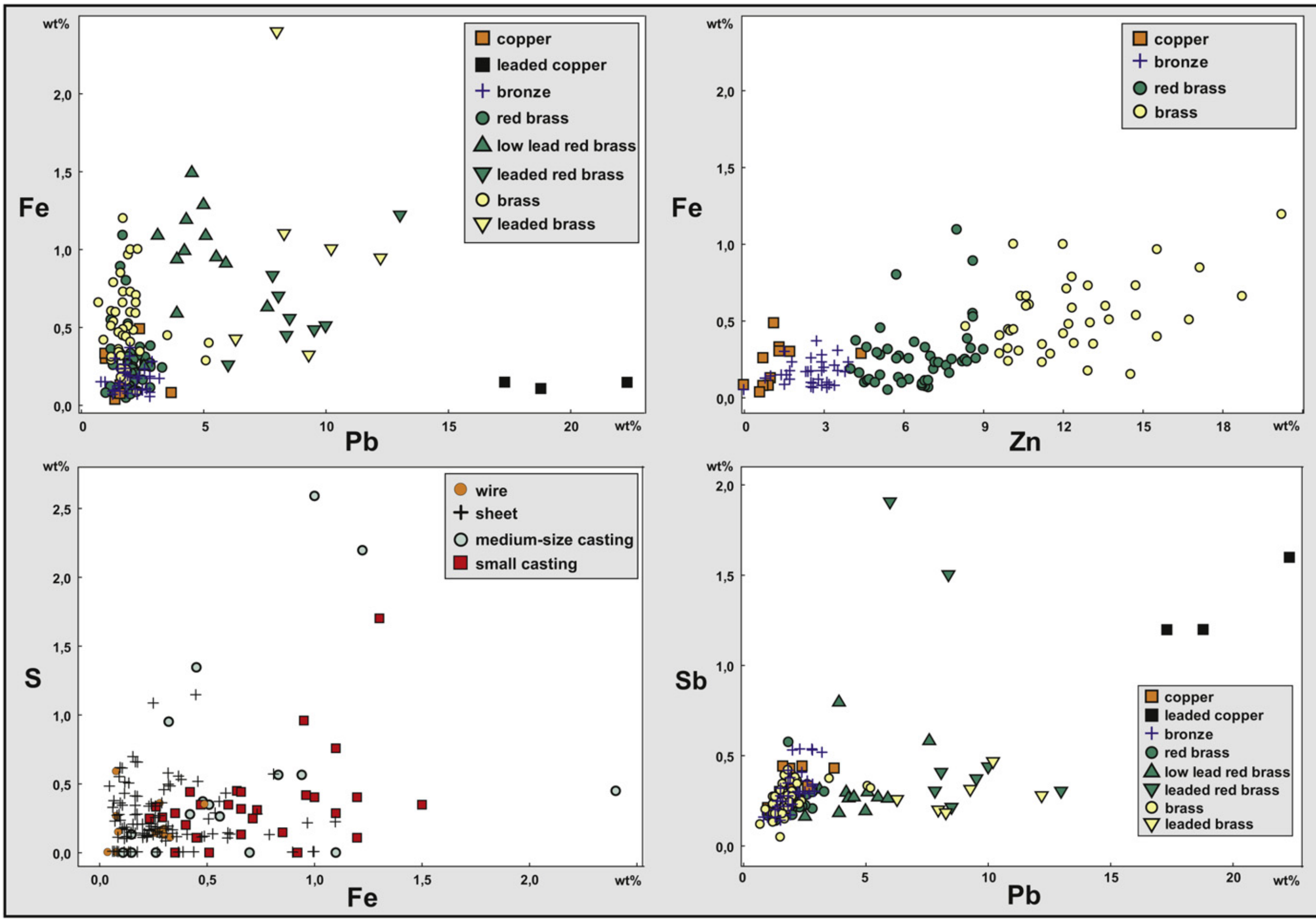

Fig. 9. Relationships between alloying elements and impurity contents in the artefacts from Hôtel de Mongelas (wt %): Fe and Pb contents sorted according to the type of alloy. The transition from Brass to Leaded brass shows the same linear dependency of Fe on Pb as the one observed for red brass and leaded red brass; the low-lead red brass exhibits a particular relationship; Fe and Zn contents sorted according to the type of alloy for bronze, red brass and brass. S and Fe contents sorted according to the forming technique. The cast items show the highest S contents; Pb and Sb content according to the alloy type. Note that the 5 highest Sb values are found in the medium-size castings.

most discriminating elements happen to be lead and zinc. Hence, a large majority of cast artefacts are in leaded copper alloys, while artefacts made of sheet show exclusively unleaded alloys, the upper limit staying around 3 wt% Pb. Note that an intermediate level of lead content has been highlighted in the so-called “slightly leaded red brass” of the small castings. The role of lead in enhancing the fluidity of the melt is often mentioned in the archaeometallurgical literature, yet no studies carried out so far have been conclusive. Preliminary experimental studies on several tin bronzes (Young, 1967) show that lead addition up to 2 wt% gradually improves the fluidity of the 1250 °C melt, whereas further addition has no discernable affect. Recent experimental investigation on tin bronzes (Mille et al., submitted for publication) prove to be even more negative, where lead was shown to yield no effect at all on tin-bronze fluidity. Yet, as stated by the authors, the experimental set-up greatly influences the results and further tests need to be

Table 5
French copper alloy nomenclature as encountered in various medieval texts, and their probable meaning.

	Latin			Old French				
12th–14th c.	Aes	Cuprum	Aurichalcum	Laiton	Archal	Cuivre	Airain	Mitaille
Theophilus 12th c.	Cu alloys	Cu	Cu–Zn					
Encyclopedia (Vincenti) 13th c.	Cu and Cu alloys	Cu alloys with Zn						
Albertus Magnus De mineralibus 13th c.	Cu and Cu alloys	Often Cu non alloy	Cu–Zn Cu–Zn–Sn Cu–Zn–Sn–Pb?					
Livre des metiers by E. Boileau (Paris) end of 13th c.				Cu–Zn? Cu–Zn–Sn? Cu–Zn–Sn–Pb?	Cu–Zn (Sn?) without Pb	Cu and Cu alloys	Rare	
Notarial records and accounts 14th c.–15th c.	Cu alloys	Cu alloys	For brass wire only	Cu–Zn Cu–Zn–Sn Cu–Zn–Sn–Pb?	For brass wire only	Cu and Cu alloys	Cu alloys	Scrap Cu alloys

Table 6
Elemental composition of the three items of Hôtel de Mongelas made of pure copper (wt%). The mean content of the so-called copper alloy is indicated for each element. Please refer to Table 3 for the standard deviation.

Designation	Inv #	Cat #	Cu	Zn	Sn	Pb	S	Fe	Ni	As	Ag	Sb	Bi
Casting waste	1061-19	292	98.3	<0.10	0.034	1.3	<0.03	0.01	<0.005	0.14	0.029	0.14	<0.02
Small casting	1077-3	233	96.2	<0.02	<0.004	1.2	<0.05	0.005	0.058	0.51	0.18	0.65	0.28
	1100-1	222	98.4	<0.2	<0.006	1.3	<0.1	0.012	0.05	<0.03	0.051	0.16	<0.02
The "copper" composition			93.5	1.2	1.9	1.9	0.2	0.2	0.06	0.5	0.09	0.3	<0.04
			1.9	1.1	0.6	0.8	0.2	0.1	0.02	0.07	0.02	0.10	

carried out. Moreover, the quite comprehensive survey carried out by the authors on existing archaeological and historical evidence, in this example large antique bronze statuary, clearly points towards a correlation between lead content and thickness of the metallic wall (Mille et al., submitted for publication). As far as modern industry is concerned only exclusively phosphorized copper alloys have been tested, which is highly misleading given the prominent role of phosphorous in controlling fluidity (Hanson and Pell-Walpole, 1951; Smithells, 1967). In any case, the relatively high Pb contents (more than 6 wt %) in our so-called leaded alloys may not have been added for reasons of fluidity. As far as casting is concerned, these high Pb contents may, in turn, have had a role in reducing the steam absorption and thus the porosity perhaps reducing the hydrogen solubility, as reported by Hanson and Pell-Walpole (1951, pp. 135–136) for 5 wt% tin bronze with 20 wt% Pb and on two sorts of red brasses (7/5/2 and 5/5/5 Sn/Zn/Pb wt%). Porosity may have been quite an important concern at least for medium-size castings, in particular for vessels produced to contain liquids. On the contrary, most sheets are made of unleaded bronzes, certainly because of the deleterious effect of lead on mechanical properties during plastic deformation.

Interestingly, cast artefacts without appreciable zinc content are quite rare (Table 4), hence only three casting waste samples exhibit a so-called leaded copper composition with significant levels of antimony. All the other castings are red brass or brass, with more than 6 wt% Zn. Conversely, low zinc copper alloys (less than 3 wt% Zn) are often observed within the sheet, together with red brasses and brasses. The preference for zinc-containing alloys for casting may not be surprising: Craddock (1981) had already noticed the benefits of an addition of 1–4 wt% of zinc as a deoxidizing agent, as reported by modern founders in Patan, Nepal. Moreover, zinc is known to enhance fluidity of

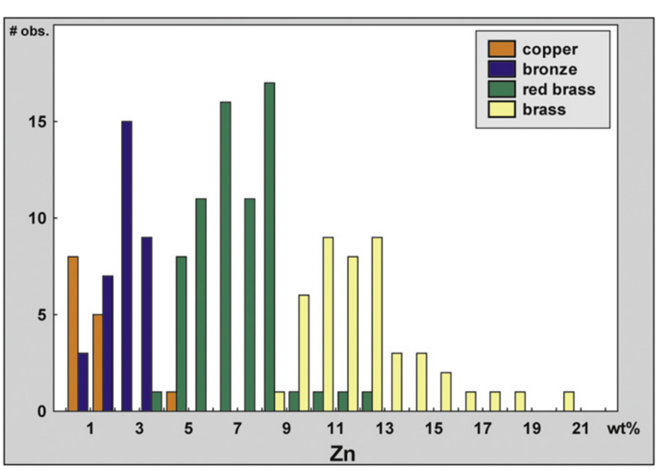

Fig. 10. Zinc distribution (wt %) within all artefacts analysed, according to the alloy types. Leaded and unleaded alloys have been grouped together in one single type of alloy.

copper-based alloys by yielding a smaller freezing range when compared to that of tin bronzes. Zinc addition is a common practice at the precision foundry of Vimeu in France (Jean-Marie Welter, pers. comm.). It is quite interesting to note that according to modern concerns (Schmidt and Schmidt, 1992), the so-called leaded red brass (alloy C83600 in the American standards, referred to by one of its common names—85–5–5–5 or ounce metal, containing 5 wt% of Zn, Sn and Pb) is rated very high in castability (2 on a scale from 1 to 8, see Table 2 in Schmidt and Schmidt, 1992) and constitutes the largest tonnage of modern copper-base foundry. If one recalls that the term castability is related in modern industry to the ability to reproduce fine details on a surface (Schmidt and Schmidt, 1992), it may not be surprising that such a property would be important in the successful casting of small dress fittings.

That said, the popular 85–5–5–5 alloy is labelled as one of the "workhorses" of copper alloys for casting, thus it has been relegated to ordinary modern foundry practices (Schmidt et al., 1992). As far as the household medieval castings studied here are concerned, their simple shapes and low dimensions may not have required high constraints on the quality of the metal to be poured. More generally, the mechanical and physical properties might not have been of primary importance in selecting the copper-based alloys that were used for late medieval day-to-day items. Indeed, such production – and notably the hammered items studied here – did not undergo heavy mechanical loading during their forming, nor during their use. This is further seen by the fact that in the present study, the sulphur contents do not show any variations that could be correlated to the forming technique (Fig. 9). Yet, whereas impurities and particularly sulphur are known to be deleterious for plastic deformation (see notably the recent study of rolling properties of 6 wt%- tin bronzes (Gordon and Knopf, 2006), experimental cold hammering tests on 9 wt% tin bronzes have shown that high levels of sulphur do not rule out plastic deformation: at the most, deformation rates between two annealing treatments have to be lowered (Andrieu et al., 2000).

The colour – or more generally the visual appearance - of the different alloys might have been of much greater concern. Once again, one may complain about the lack of rigorous and objective quantification of the effect of the different alloying elements on the colour of copper alloys. One reason for this may be that the physical measurement of colour on metals is actually not straightforward (Bourgarit, 2003), yet the influence of zinc on the gold-like appearance is well perceived at least qualitatively. At Hôtel de Mongelas, it seems that the largest and thus most visible dress fittings obtained by hammering bear the largest amounts of zinc (Thomas, 2009, p. 533). Such a tendency had already been observed on medieval castings from Germany and the United Kingdom (Brownsword, 2003, 2004), where brass and high zinc contents were found in visible objects such as candlesticks and aquamaniles for example, while cooking vessels, mortars and weights exhibited leaded bronze compositions.

4.2. Economic constraints

In Late Medieval Europe lead was a by-product of silver production and was thus certainly by far the cheapest of the four main metals encountered at the time. Yet, we must admit that the lack of written records, such as an inventory of costs, does not allow for a sound comparison between lead and copper costs. However, lead is certainly cheaper than tin (Benoit, 1985) and this may be one significant reason why lead has been added in large quantities in the largest objects studied during the present work, namely in the waste referred to as medium-size castings.

The high-antimony contents encountered in the leaded alloys recall the copper-lead alloy pointed out as *caldarium* for British cauldrons and skillets (Dungworth and Nicholas, 2004), although in our case the red brass demonstrates the occasional presence of antimony (Fig. 9). Is such an alloy a by-product of the silver production by liquation, as proposed by Dungworth? One thing is fairly sure: in this case it is a very impure metal which, for this very reason, might certainly have been cheaper than a purer copper. We know indeed that different qualities of copper were on trade in Europe, as observed in Venice (Braunstein, 1977). As previously seen by Dungworth, in our study such low-quality metal is only found in some of the high lead-bearing casting waste. This waste has been shown to pertain very probably to cast vessels.

Speaking further regarding copper quality, one may distinguish between different levels of iron and sulphur content (Table 3) depending on the type of alloy and the destination of the production. Hence, we encounter the less pure metals (labelled as xxx-BB in Table 4) exclusively within data acquired from the castings. The example of lead suggests this as a deliberate attempt to lower the cost of raw material (e.g. copper) for production involved in the largest quantities of metals. Refining a metal has indeed a cost. That said, the general impurity level remains fairly high for all the production (more than 1wt % total for all impurities, including primarily iron, …). Only two small castings (cat# 222 and 233) and one cast waste (cat# 292) are made of a quite pure unalloyed copper (more than 96 wt% Cu). This unusual composition, with a high level of Bismuth (0.3 wt% for the cat# 233), caused their removal from the statistical analysis (Table 1), since all the other small castings from the workshop are indeed alloyed coppers, namely brass or slightly leaded red brass with less than 85 wt% Cu (see Fig. 5). Does it mean that the Parisian workshop was involved in the occasional production of high quality items for particular customers? The derisory small quantity of metallic artefacts recovered bearing this composition, and the typological ubiquity of the production (one of the small casting is a nail, cat# 233, the other one may be identified as the extremity of a pommel, see cat# 222, i.e. #34 in Fig. 1) prevents any firm answer. Yet, the recovery of two fragments of rock crystal and of a number of small glass cabochons clearly testifies for the production of luxury goods (Thomas, 2009: 433–443 and 940–942).

That said, the most prevalent economic concern regarding the practice of alloying within the Parisian workshop might have been the control of the zinc content. This will be further discussed in the following section. Before this, the alloying modes will be discussed.

5. Discussion: metal supply and alloying modes

The variety of alloys in use raises the question of the metal supply system. In particular, what alloys were being produced on-site and which were available through trade? Who is creating the alloys and how? Which alloys are circulating? The analytical work carried out at the workshop of Hôtel de Mongelas offers a unique opportunity to try to address some of these issues.

For each of the eight types of alloys present at Hôtel de Mongelas, different levels of alloying element (Sn, Zn and Pb) and impurity (iron and sulphur) content have been identified leading to a five-letters code (Table 4). Based on the evolution of these labels from one type of alloy to the other and on the underlying analytical results, we may propose several different metal supply modes for the Parisian workshop (Fig. 11), with a common postulate: most alloys are produced On-site. Brass was the only exception and probably not synthesized within the workshop. Indeed, given the dominating presence of zinc-containing copper alloys on the site, had brass cementation been routinely carried out it would have left considerable evidence. Yet, among the numerous crucible fragments recovered at the site (Katona et al., 2007), only one artefact may be interpreted as coming from a brass cementation vessel, as shown by its purple colour paste due to relatively high amounts of zinc (see Picon et al., 1995). In this example, a steady decrease from 23 wt% Zn at the inner surface to 5 wt% Zn 3 mm inside the ceramic wall has been measured by SEM-EDS on a polished cross section; this resembles the impact of brass cementation on refractory (Bourgarit and Thomas, submitted for publication). Moreover, both the associated crucible material and typology happen to be quite uncommon within this particular archaeological site.

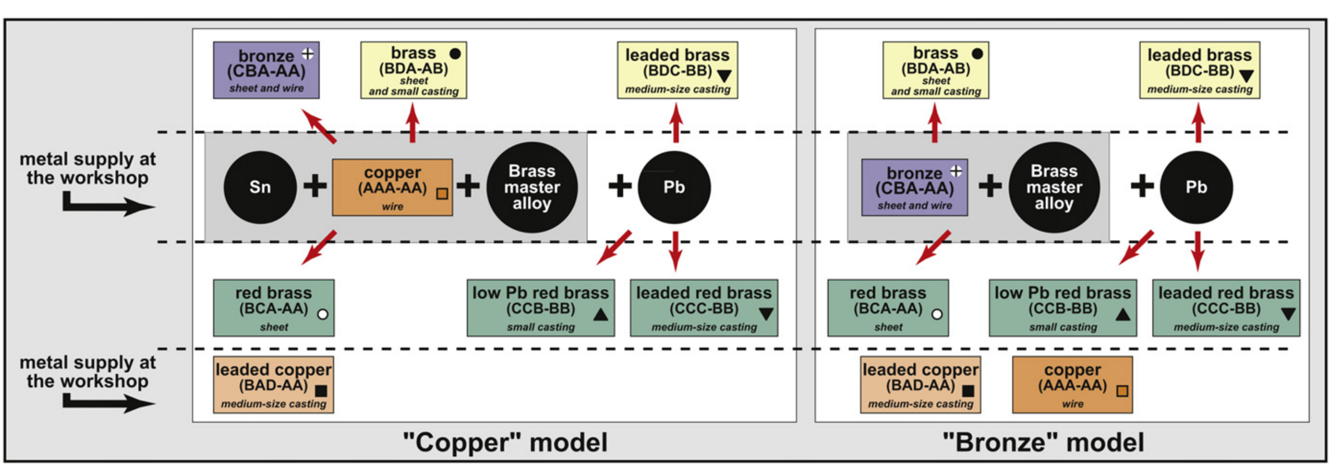

Fig. 11. The two hypothesis of alloying modes at Hôtel de Mongelas: "copper" mode, "bronze" mode.

The following section presents the two extreme hypotheses of alloying modes.

5.1. Copper as base metal

One may propose that the so-called "copper" is at the centre of the system (Fig. 11). The composition code of this "copper" is AAA-AA (for its levels in SnZnPb–FeS, see Table 4). In order to achieve the other groups of compositions, tin, lead, and zinc are added to reach the levels B and even D for the lead and the zinc (see Table 4). Since no clear correlation could be drawn between any of these three elements, it is assumed that tin, lead, and zinc are added separately. Tin and lead are added as pure metals, whereas zinc enters the melt as a brass master alloy. The composition of the brass master alloy is quite difficult to estimate given the wide range of all compositions. This point will be discussed more in detail in section 5.2. The brass master alloy is diluted by tin, lead and copper additions. Leaving the lead aside, the dilution path by tin and copper may be drawn on a binary diagram Zn–Sn as a complex system of lines (Fig. 12). One may distinguish between two systems. On the one hand a main axis of brass dilution by copper appears as a line joining the "copper" pole and the initial brass composition, that is somewhere on the vertical axis (no tin). On the other hand, several horizontal lines representing the tin addition may be drawn starting from the main axis of brass-copper dilution.

Yet, such a scheme appears as quite improbable. First, the small and quite precise additions of tin (about 1–2 wt%) in order to transform the brass master alloy into brass, red brass, or bronze appear as a complex practice. Moreover, since the original copper already bears some tin (2 ± 0.5 wt %), the gain of such small additions of tin may be questioned. Finally, the overall scheme might not have been economically viable. The so-called bronze alloy is actually nothing more than a "dirty" copper (see Fig. 5 and following discussion). One wonders then why expensive metals such as fresh copper, fresh brass and – may be even more expensive – fresh tin would have been diluted into common metals such as bronze, red brass or low-grade brass.

Note that two metals have been omitted in this scheme, namely the leaded copper, and the very pure copper. Due to its high antimony content and low levels of both iron and sulphur,

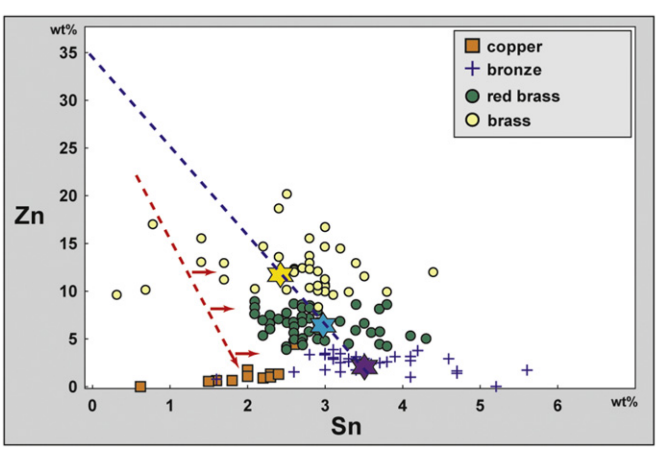

Fig. 12. Sn and Zn contents sorted according to the type of alloy for the three alloys bronze, red brass and brass. For each type of alloy, the mean value in tin and zinc has been plotted as a large coloured star. The 3 stars have been joined by a line in order to infer the zinc composition of the brass master alloy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the leaded copper cannot be obtained by addition of the same lead as the one proposed for the other alloys (Fig. 9). This particular alloy may have actually entered the workshop, possibly as a by-product of silver extractive metallurgy as discussed earlier.

The very pure copper may have been obtained by refining the so-called copper at the site. At least basic thermodynamic considerations do not contradict such a view. Indeed as far as we know, during medieval times copper refining was exclusively carried out by thermal-assisted selective oxidation, as notably described by Theophilus (Dodwell, 1961: 125–126). According to the Ellingham oxidation diagram, such a process may pertain to the lowering of iron and tin content, as observed here. Yet, one shall remark that none of the three pure copper items may have come from the same source, as demonstrated by the variations in impurities (see notably the bismuth, arsenic and nickel contents in the Table 1). Thus, this particular anecdotal metal might correspond to a very specific supply, if any.

5.2. Bronze as the base metal

A dilution path from brass to the so-called bronze can be seen that is quite linear on a binary diagram Zn–Sn (Fig. 12), thus pointing to a much simpler alloying system than the one involving copper. Hence, only three main metals are involved instead of four (Fig. 11) and in particular no specific tin supply is required. The starting bronze is either used for the forming of some sheets and wires, or further alloyed with zinc for other applications.

In order to determine the zinc composition of the nominal brass master alloy, a zinc-tin linear relation has been looked for while forcing the line to pass through the mean bronze composition (Fig. 12). Yet, due to the wide scattering of tin and zinc contents, the regression coefficient between the theoretical line and the experimental points has shown to not evolve significantly whatever the range of zinc content in the nominal brass master alloy (values ranging from 15 to 40wt% Zn have been tested). Consequently, attempts to determine a precise estimate of the original brass master alloy composition have been in vain. One must be content with a quite basic approach consisting in joining the three barycentre of the three alloy groups (Fig. 12). Still, one may note the perfect alignment of the three points. This leads to a 35 wt% Zn brass master alloy, which shall not be considered more than an indicative value. Therefore we will not comment much on this estimate. One may just remark that such a zinc level is quite larger than those encountered in the few medieval brass ingots analysed so far (Bayley et al., 2011), where the zinc level stays around 20–25 wt%. That said, recent experimental field trials, sticking closely to the late medieval archaeological evidences from several bronze workshops of the Mosan valley, have led to 35 wt% zinc brasses, with a very good repeatability (Bourgarit and Thomas, 2011, submitted for publication). Note also that according to this model, an approximate linear extrapolation (Fig. 8b) would lead to a brass master alloy bearing around 1.5 wt% Fe, which may be compatible with our experimental observations as well.

As far as lead alloying is concerned, pure lead may have been added in order to produce the highly leaded alloys, namely the leaded brass and the leaded red brass. Occasionally, some high–antimony leaded copper – the so-called *caldarium* probably purchased as such as inferred for the previous alloying model - might have been used as a lead source, as notably seen in two slightly leaded red brass examples that are rich in antimony (Fig. 9). Moreover, while the pure lead may have incorporated some iron, the particularly high levels of iron in the slightly leaded red brass when compared to the one in the unleaded red brass (Fig. 9) may come from the initial bronze (or brass) as well, which would mean that a lower grade bronze (or brass) with high levels of iron would have been used. The possibility that refining of this low-grade metal was carried out at the site cannot be totally discarded although if so, one would have expected a clearer concomitant lowering of the content in sulphur (and arsenic as well), which is not the case. Anyway, such use of cheaper metals (high in iron and occasionally *caldarium*) for the making of slightly leaded red brass raises the question of the status of this particular alloy.

Inversely, a third quality of copper shall have been purchased, namely the so-called "copper" alloy. Yet, this copper is only found in the wire obtained by plastic deformation, whereas the cast wire is of bronze. Thus, one may wonder if the Parisian workshop did not directly purchase ready-made copper wires instead of forming the copper ingots into wire.

The situation for the sheet is much clearer. Some of the analysed sheet is made of exactly the same brass as the one used for casting. This clearly testifies for hammering at the site, as further demonstrated by the recovery of waste of hammered strips (Thomas et al., 2008).

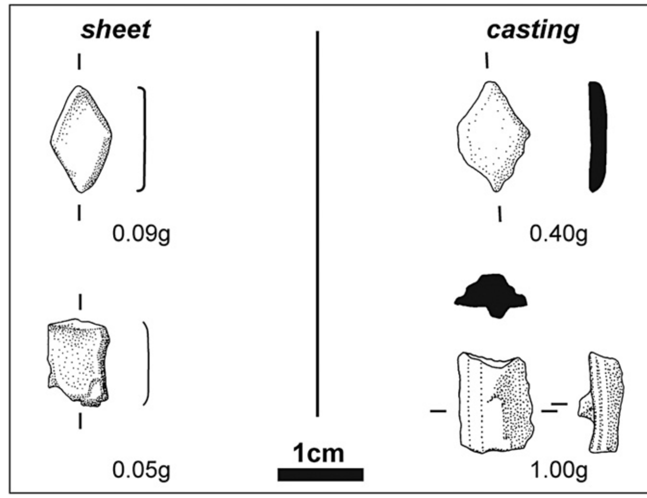

Fig. 13. Cast and sheet belt mounts produced at Hôtel de Mongelas showing the differences of weight. Note the weight ratio around 4 to 1 between cast and sheet.

5.3. Fresh metals versus recycling

The so-called bronze of Hôtel de Mongelas, with its intermediate contents in the three most common alloying elements in medieval times (3.5 ± 1wt% Sn, 2 ± 1 wt% Zn and Pb see Fig. 4), may be reasonably considered as scrap metal. Note that the copper actually yields a similar fingerprint as the one of scrap metal. Thus, whatever the model proposed, a bipolar alloying mode seems to merge, consisting mainly in the mixing of a cheap scrap metal and a fresh brass master alloy. The zinc level thus refers more or less directly to the degree of recycling, with increasing zinc contents testifying for the increasing use of "fresh metal", namely brass, as already suggested by Caple (1995).

It would then not be surprising that bronzes – that is cheap scrap metal- are almost exclusively encountered in part of the small sheet artefacts from Hôtel de Mongelas (Table 4), that is actually in the less valuable production. As shown indeed by gild statutes, laws or ordinances (see for example the Parisian haberdasher of 1324 devoted especially for dress fitting statutes (Lespinasse, 1892, 245)), "hollow" and thin items made of sheet are much less valuable than solid casts. In our corpus, the "oeuvres creuses" obtained by stamping happen to weigh around ten times less than the castings they are imitating (Fig. 13). Inversely, castings are mainly made of alloys bearing significantly more zinc that is more fresh metal, namely red brass or brass with zinc contents often above 5 wt% and reaching frequently 15 wt% and more (Table 4). That said, if one plots the different alloy types in a ternary brass–bronze–Pb diagram according to the bronze-dilution model proposed (Fig. 14), the relative quantities of master brass input appear quite small whatever the destination (less than 1/5 of the total). Such a wide use of scrap metal – and to a lesser extent of lead - is in agreement with our proposal of an economically-driven alloying practice at the Parisian workshop, which production consists mainly of low-cost day-to-day goods. Such alloying strategy relying on the dilution of an expensive metal, namely a brass master alloys, by scrap "bronze", a cheaper material, raises the question of the relative value of the different metals.

5.3.1. Cost of brass

The final cost of brass depends on at least four parameters: the cost of copper and/or copper-based metals, the cost of zinc ore, the brass making cost, and the transportation costs. Unfortunately, we lack of quantitative data on any of these aspects, thus any attempt to quantify the overall cost is quite in vain. Nevertheless, some qualitative observations may be carried out.

The cost of copper might have depended upon its provenance, notably because of the different copper qualities provided. It has been seen that the impurity pattern at Hôtel de Mongelas shows a quite remarkable steadiness (Fig. 8), which obeys the Equation (1). This may pertain to the short duration of the workshop, which is less than thirty years (Thomas, 2009). Does this similarity point to a unique copper source for the whole Parisian Basin? Unfortunately, the few impurities put into light in our objects are rather ubiquitous and may pertain to a number of copper mines in activity at the beginning of the 14th century. Moreover, the possibility of mixing different coppers shall be taken into account, especially in the frame of the alloying modes suggested for the workshop where a brass master alloy is diluted by scrap bronze. Thus it seems of little value on the basis of our results to try to

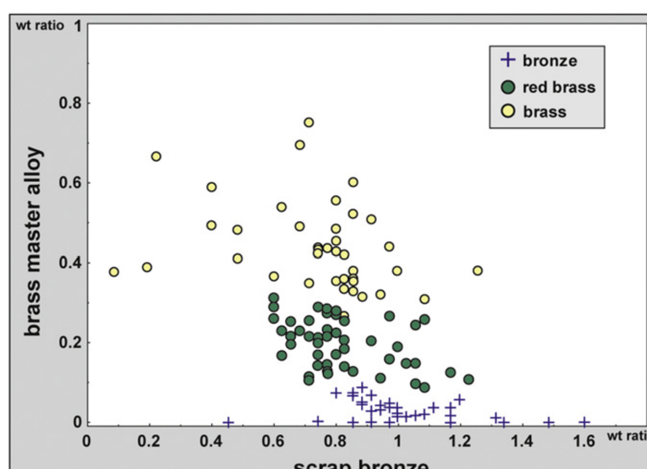

Fig. 14. Composition (weight ratio) of the different alloy types according to their relative amounts of the two main metals, namely brass master alloy (here inferred to bear 35 wt% Zn) and bronze (see composition in Table 3). Since the composition of both metals shows some discrepancy (we have considered here the mean value), the sum of both ratio frequently differs from 1.

localise the exact provenance of the Parisian copper(s), not speaking from the fact that the chemical fingerprint of the copper produced in medieval mines is far from being systematically and unambiguously defined.

Yet, one may at least discard some of the most productive medieval copper mines known so far. For instance, the composition of the Falun copper in Sweden, which relies mainly on the analysis of five ingots (Forshell, 1992: 99) shows relatively high silver and low arsenic contents which do not match the Parisian metal. Note that the Parisian metal impurity pattern is very similar to the one of the ten objects stemming from Sweden in the 11th to 13th c. analysed by Werner (Werner, 1982). The Rammelsberg in the Harz Mountain may not have been a better candidate (Klappauf, 2004; Bartels et al., 2007), although the only characterization of the medieval exploited ore consists of the analysis of a number of medieval prestigious items belonging to the nearby Goslar (Laub, 1993), which were not necessarily made with local copper. The Goslar items revealed much higher levels of silver than in our samples. The high nickel content (up to 1wt% or more) of the copper stemming from the Mansfeld Kupferschiefer rules out this source as well (Meyer, 1905-1909, Werner, 1977).

Unfortunately, smaller deposits are often less documented, notably on the geochemical point of view, and therefore are often not considered as the potential source. Hence, nearer deposits might have provided the French capital as well, such as those from the Vosges and the French Alps, for which at least 14th c. exploitation has been documented (Benoit and Braunstein, 1983).

Note that recycled copper-based alloys including brass cannot be excluded from the possible raw material used to make fresh brass. This is at least technically feasible, as demonstrated by experimental simulation where alloys containing up to 10 wt% tin and 5 wt% lead were tested and led to high zinc brass by the cementation process (Bourgarit and Thomas, submitted for publication). This is also clearly seen in later periods, notably in some 18th c. German brass plants (J.M. Welter, pers. comm.).

No clear comprehensive picture of the brass production centres in Europe at the beginning of the 14th c. is yet available. Of course the Mosan Valley remains a good candidate; the cities of Bouvignes and Dinant are famous for their manufactured brass products (Thomas et al., 2010). The presence of the zinc ore calamine in this area clearly contributed to the development of the copper industry, although to date there is no evidence of the export of brass ingots. The other possible medieval sources of zinc are not yet identified. However, while almost nothing is known about the trade of brass, there are numerous written records on calamine trade (Thomas, 2009: 249–251). Albertus Magnus was writing in the 13th century that he saw the production of brass "in Paris and Cologne and other places" (Wyckoff, 1967:224). Fresh brass or zinc ore could be imported by Parisian brokers, as appearing in the 1327 and 1420 Parisian boilermaker's statutes (Lespinasse, 1892: 500 and 505). Anyway, our analytical data does not allow us to discuss the provenance of zinc ore or brass as a fresh metal. It is thus difficult to estimate the cost of brass that was paid at the Parisian workshop. Note that transportation of raw material alone used to increase the initial value by 10% or more (Benoit, 1985).

5.3.2. Origin of scrap bronze

In the "bronze-dilution" model, the so-called scrap bronze is at the very centre of the metal supply system. Thus, the origin of scrap bronze is a crucial issue. Note that this scrap bronze represents the unique source of tin at the site (mean composition 3.5 ± 1 wt% Sn, 2 ± 1 wt% Zn and Pb). The highest tonnage of tin-containing copper alloys circulating in Late Medieval Europe might have been cast vessels and bells. As already discussed, a majority of European medieval cast vessels analysed so far bears high quantities of lead with frequently much more lead than tin, and often high amounts of antimony and/or arsenic.[1] At Hôtel de Mongelas, the scrap bronze exhibits more tin than lead, with relatively low levels of arsenic and antimony. Consequently, in order to achieve the composition of the Parisian scrap bronze, cast vessels shall have been mixed with a metal containing much more tin than lead, and small quantities of arsenic and antimony. Bell bronze might have been a good candidate with its *circa* 20 wt% tin and less than 1 wt% lead and relatively low As and Sb (Bayley et al., 1993; Drescher, 1992; Dungworth and Maclean, 2002; Giannichedda et al., 2005; Giot and Monnier, 1978; Neri, 2004). Only zinc is missing. Large castings pertaining to higher standards such as ewers and candlesticks, together with large hammered vessels such as basins and weighing plates might have provided large quantities of zinc, since most of them are made in brass or leaded brass (Brownsword, 2004; Thomas et al., 2010, submitted for publication).[2] Smaller artefacts such as those produced at Hôtel de Mongelas might have provided all the metals entering the scrap composition as well – and in particular the exact bronze composition. Yet, to estimate the relative proportion of each type of item (cast and hammered vessel, bells, small day-to-day items) into the recycled metal batch, one needs to estimate first the relative quantities of each type produced at a macroscopic level – for example at the scale of a big city such as Paris - and, more importantly, the approximate life-time of each type of item. This is quite difficult at the present state of our knowledge. Note that considering only the large castings for recycling leads to a mix which is not economically viable.[3]

One may wonder whether unalloyed copper could be added to the scrap before being purchased. This might explain the low levels of alloying elements. This would also facilitate the control of the composition. Indeed, according to the "bronze" model there is only one type of scrap metal entering the site, with a composition quite narrow in lead and tin, although it may have consisted of different quality grades depending chiefly on the iron content, as seen for the slightly-leaded red brass. This would confirm the written records, especially guild's rules, which tend to show that the metal market was quite well controlled by some brokers who were elected by the guild, at least in Paris at this time. Thus here recycled metals would have belonged to raw material "standard". It may correspond to the so-called "*mitaille*" present in several French texts (see Table 5), although the very nature of the raw material designated thereby remains highly speculative. Note that the composition of the bronze is not much different than the one of the modern American "workhorse" for casting, the 85-5-5-5 alloy (5wt% of Sn, Pb, Zn, see Schmidt et al., 1992).

[1] See for example the mean composition of Late Medieval and Post medieval cast vessels recovered in Britain (c. 5 wt% Sn, 14 wt% Pb, 0.6% Zn, 5%Sb, and 1%As, after Dungworth and Nicholas, 2004; Table 1), or the mean composition of the Late Medieval Mosan cast vessel made in leaded bronze (6 cauldrons and ewers analysed by the authors: 7 wt% Sn, 13 wt% Pb, 0.4% Zn, 3%Sb, and 1%As, see Thomas et al. (submitted for publication)).

[2] The mean composition of the Late medieval Mosan brass cast vessel analysed by the authors (6 items) yields 2 wt% Sn, 9 wt% Pb, 16% Zn, 0.5%Sb, and 0.6%As see Thomas et al. (submitted for publication).

[3] Assuming the following mean composition of cast bronze vessel (7wt%Sn and 15 wt% Pb), cast brass vessel (15 wt% Zn and 10 wt% Pb), and bell (20wt% Sn), the scrap bronze from Hôtel de Mongelas would be obtained by mixing one part of bronze vessel, three parts of brass vessels and three parts of bell. Yet, brass vessel seems to be a quite expensive item….

6. Conclusion

Some 161 late medieval copper-based day-to-day items stemming from a recently excavated 14th c. AD metallurgical workshop located in Paris have been analysed. The very question of the existence of controlled alloy recipes has been discussed, leading to eight well-defined compositions. The alloying choices have been shown to refer to various factors, the most important one being economics. Technological constraints have surely been taken into account by the craftsmen for some specific aspects as well, such as the control of relatively low levels of lead in hammered artefacts, the input of zinc in order to enhance the castability for small dress fittings, or the mastering of colour by zinc control. Yet, the production of most day-to-day items studied here obviously did not require strict metallurgical properties, thus economic concerns were likely of greater importance than technical constraints. Hence, the variety of alloys put into light seems to pertain mostly to a variety of economic considerations, with zinc and lead acting as the main levers. On the one hand, cheap metals bearing large quantities of lead or metallurgical by-products such as antimony bronzes are clearly used for down-market production. Similarly, bronzes with relatively low levels of zinc, assimilated as scrap metal are found in small sheet artefacts: according to western medieval standards, these kinds of dress accessories were of lower value than plain casts, the latter being made of metals bearing higher amounts of zinc, namely red brass or brass. In all cases, relatively large quantities of lead are added to lower the metal cost, with an emblematic limit of 6 wt% Pb marking the border between leaded and unleaded alloys. This border may be linked with the rules of the craft, such normative constraints corresponding to the unleaded alloys as specified by the statutes of the 14th c. Yet, the question remains of how a 6%wt lead limit could be controlled. Further studies including mechanical and chemical experiments are planned.

The type of product, and more generally the very nature of the market to which the production is intended, may influence the alloying strategy in a complex manner. Hence, the medieval production units seem much more adapted to the market than previously thought, as seen here on the particular example of the Parisian workshop of Hôtel de Mongelas. In order to sustain such a strategy, the workshop is organised more as a small industrial plant rather than as a craftsman shop, as previously shown by archaeological and historical evidence (Thomas, 2009: 917–953; Thomas and Bourgarit, 2006; Thomas et al., 2008). Among the main features characterizing the particular organisation, three are particularly well documented by the analytical results presented here. First, the presence of heavily leaded alloys among unidentified casting waste has indicated the production of medium-size castings, probably cast vessels, thus greatly enlarging the variety of types produced by the workshop. Second, the large range of alloys in use and the variety of the raw metal supply mode, from “fresh” brass master alloy to scrap bronze and internally recycled leaded copper may be mostly interpreted as the capability to face a large range of demands. Note that the few pure copper artefacts recovered at the site may attest to the production, certainly marginal, of some high-ranking products alongside the more usual day-to-day items. Finally, the complex mode of metal supply and alloy production proposed, which relies mainly on the controlled mixing of “fresh” brass, lead and scrap bronze, adds one more metallurgical skill to the already numerous activities carried out at the workshop. Almost all metallurgical know-how except metal extraction – and probably brass cementation - is thus represented, including alloying, hammering, moulding and casting.

That said, one potentially important aspect has been discarded from the discussion, namely the part of cultural determinism on the alloying strategy – note that all along this paper we have favoured the concept of alloying *habit* or *practice* rather than the concept of alloying *recipe*. The main constraint on such an approach is that the archaeological record lacks comparable data. The main data provider so far comes from studies undertaken in England (Brinklow, 1975; White, 1982; Heyworth, 1991; Blades, 1995; Caple, 1995; Brownsword, 2004; Dungworth and Nicholas, 2004), yet despite the huge number of sites excavated, none of them can be directly compared to Hôtel de Mongelas; which is to a production site with an activity spanning a very small period (around thirty years) and providing us with a very large assemblage of small household items. In order to overcome “time dilution” bias, we aim to discuss local or cultural particularism in a forthcoming paper, where analyses stemming from different late medieval sites of the Parisian basin over a larger span of time (13th–15th c.) will be presented.

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