Original Article
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PRINTED CIRCUIT BOARD RECYCLING: PHYSICOCHEMICAL AND ECONOMIC ANALYSIS OF METALS

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Abstract

This study aims to present the characterization of five different types of printed circuit boards (PCBs) for use in future recycling processes. PCBs used: motherboards, lead free motherboards, video cards, memory and printer cards. The comminution of the circuit boards was performed using blade mills and hammer mills with 9mm and 6mm meshes, respectively. Throughout the physical processing, analysis was made with stereoscopic optics to ensure that the correct materials had been released. The pre-magnetic separation parts were given a granulometric classification followed by acid digestion and loss on ignition tests. The composition of the PCBs studied varied from one board to another, with the metallic fraction being the main constituent of lead free motherboards, video cards and printer PCBs, while the motherboard and memory cards contain a greater volume of polymeric and ceramic material constituents respectively. Three samples showed similar behavior in granulometric distribution with a tendency of material accumulation in the sieves with wider meshes and, in two of them the highest percentage of material was retained by those with smaller screens. Cu was the metal found in the greatest concentration. Silver, gold and copper were the metals with the highest value percentages.
Keywords: Printed circuit boards; Characterization; Recycling; Economic analysis.

1 INTRODUCTION

The unbridled consumption and the accelerated pace of the development of new technologies coupled with the decrease in the equipments' life expectancy and the increase in the occurrence of defects in electrical and electronic equipment, brings a growth in electronic waste generation as a consequence [1]. In 2009 it was estimated that there was a generation of between 25 and 30 million tonnes of electronic and electrical waste [2].

This waste from electrical and electronic equipment is composed of different devices that contain a wide variety of components, which in turn have numerous elements and substances. These facts make the classification of electronic scrap quite complicated, since such waste cannot be placed in a single class.

Additionally, the tendency towards the replacement of harmful elements by another class of less dangerous elements in the manufacturing process has become common practice. For example, ten years ago the amount of hazardous components that were used in the equipment was greater than the amount that is used nowadays and, certainly, the amount that will be utilized in the next decade will be less than today [3,4].

To this end, new technologies are being developed in the manufacturing processes of consumer electronics, resulting in new global policies relating to solid waste. From this point of view it can be observed that the European WEEE Directive (Waste of Electrical and Electronic Equipment) [3] and the RoHS (Restriction of Certain Hazardous Substances) [4], restricts the use of substances such as lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, diphenyl ether and polybromides in the manufacture of electrical and electronic equipment because these substances are considered dangerous [5]. In the area of new technologies, the development of new flame retardants and lead-free solder have already been cited as alternatives to some previously used components.

Furthermore, the composition of printed circuit boards (PCB's) is complex and depends largely on the type of equipment that is used. For example, some circuit boards may have precious metals in their composition, but another type of circuit board may not [6]. However, the reduction of material usage in various stages of PCB production, in addition to the reduction in their functions, is the trend provided by current technological advances [7].

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However, the PCBs are approximately 30% metal by mass [8], including precious metals such as gold and silver, which are the principle parts sort by the electronic recycling market, followed by metals such as copper and zinc [9].

Currently pyrometallurgy is the most widely used commercial method for the recycling of electrical and electronic PCB equipment, however, several studies have been developed for recycling by bio and hydrometallurgy processes [10,11], high-voltage electrical pulses process [12] and froth flotation process [13].

2 MATERIALS AND METHODS

2.1 Samples: Identification and Quantification of the Components

Printed circuit boards used in this research were collected by a waste electronics recycling center in the city of São Paulo – Brazil. Five different types of circuit board were analyzed, these being: motherboard, lead free motherboard, video card, memory cards and graphics card.

In order to identify and quantify the components present in the PCBs the dismantling was performed using tip pliers and then visually identified by grouping them into 10 categories according to their characteristics. The components of the groups were weighed and the percentage by mass of each category was calculated.

The circuit board substrate was observed with binocular loupes to identify whether the card was dual or multi-layer.

2.2 Physical Processing

2.2.1 Dismantling and manual size reduction

Initially the manual dismantling of the printed circuit boards was performed using pliers and a screwdriver for the removal of heat sinks, screws and electrolytic capacitors. With the aid of a manual guillotine, the boards were cut into smaller pieces so that they could fit in to the opening of the mill. This procedure was performed for all the PCBs with the exception of the obsolete graphic cards as these had arrived in reduced sizes.

2.2.2 Comminution

Made primarily by grinding the PCBs in a blade mill with a mm grill followed by grinding in a hammer mill with a 2 mm grid, with the exception of the graphic card samples, which were milled using a 1 mm grid in the hammer mill. According to Tuncuk et al. [14], the full release of copper happens with a particle size smaller than 2 mm as in larger particles there can be tunneling of Cu on the pins of the plastic components.

2.2.3 Magnetic separation

The magnetic separation of the sample was performed after grinding by the hammer mill. A dry drum magnetic separator was used at the following settings: magnetic roller speed = 27 rpm; vibration percentage of the feed 25%.

Figure 1 shows the physical processing flowchart adopted in this research.

2.2.4 Granulometric classification

Through th granulometric study of the material it is possible to analyze the behavior of materials after comminution. Granulometric analysis made of the ground samples before magnetic separation (sample - M) the screens used had the following mesh sizes: 1.000 mm; 0.500 mm; 0.250 mm; 0.125 mm; 0.075 mm; 0.0038 mm; For the graphic card samples the following mesh sizes were used: 1.000 mm; 0.500 mm; 0.210 mm; 0.125 mm and 0.053 mm. After being held under vibration for 15 min, samples were weighed and the particle size distribution curves were built.

2.2.5 Stereoscopic analysis: milling

This analysis indicates the degree of material release after milling, allowing for the identification of mixed particles and the definition of milling routes. According to

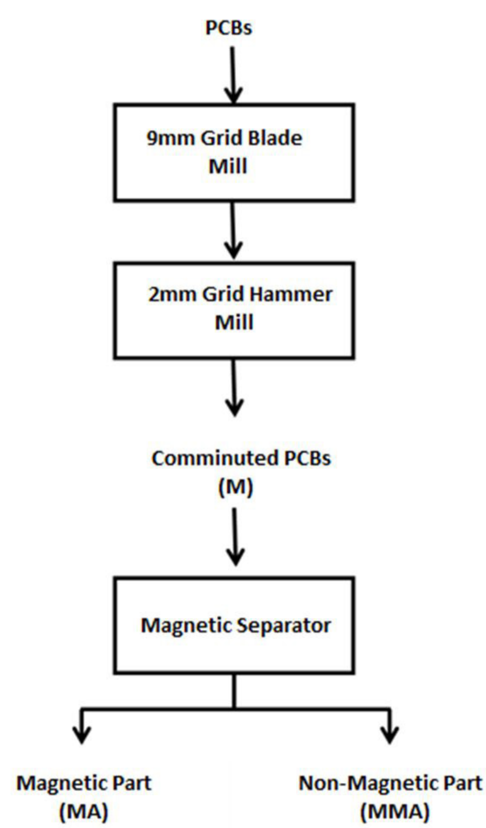

Figure 1. Flowchart of the physical processing of printed circuit boards.

Tuncuk et al. [14], losses of between 10 and 35% in metallic parts can occur on account of the insufficient release of the metals during the comminution process.

In order to identify mixed particles and material drag; an observation of the ground samples was made before magnetic separation (sample M).

Three images of each part were taken in order to avoid possible errors occuring as a result of the sample being heterogeneous. Even working with previously cut samples, the materials lacked homogeneity and three parts of the same sample were assessed.

2.3 Characterization

2.3.1 Stereoscopic analysis: cross section

The analysis of the PCB's cross-section aims to show the number of layers present.

2.3.2 Acid digestion

For the characterization and quantification of the metallic parts present in the PCBs, 5 g of the previously comminuted and quartered sample were put in contact with 50 mL of aqua regia (1 HNO3: 3HCl). After 24 hours at 25°C (±5), it was filtered using quantitative filter paper: the resulting residue was dried for 48 hours at 36°C and subsequently weighed and the loss on ignition test was performed; already the acid solution has been put for chemical analysis.

2.3.3 Loss on ignition

The loss on ignition test is designed for quantifying polymer and ceramic materials that are calculated by the weight of them being coupled to the results obtained for acid digestion. For this test we used unglazed porcelain naviculas that had been in a muffle oven at 800°C for 1 hour. The samples used in this test came from acid digestion

2.3.4 Mass balance

After the loss on ignition test, the non-volatilized material in the navicula corresponded to the ceramic materials present in the studied parts, since the residue is from the acid digestion test and the metal part was also dissolved in this. As such, the difference between the mass of the initial materials and calcined materials corresponded to the mass of the polymeric material present on the printed circuit boards.

2.3.5 Chemical analysis and aggregate value

Chemical analysis was performed by inductively coupled plasma optical emission spectrometry (ICP-OES) in equipment of the Agilent brand, model axial 710, in order to quantify the concentration of metals present in the liquors leached from acid digestion. The concentrations for the following metals were determined: copper (Cu), tin (Sn), iron (Fe), aluminum (Al), zinc (Zn), nickel (Ni), lead (Pb), gold (Au) and silver (Ag).

3 RESULTS AND DISCUSSIONS

3.1 Physical Processing

3.1.2 Component identification and quantification

After The manual destruction of the PCBs, the components were segregated, identified and quantified as displayed in Table 1.

After the segregation of the components, they were grouped according to their characteristics and type. For example, all electrolytic capacitors present on the circuit board were classified in to one group.

Even after manual dismantling some components remain on the circuit boards (items H, I and J), these components are called SMD (Surface Mount Devices). These aree capacitors, identified as Cnn, resistors (Rnn) and diodes that are already present on the circuit board base, or the bare-board.

Table 1. Identification and quantification of the PCB components

Item	Identification	% by mass				
		board Mother	Lead free *motherboard*	Video card	Memory	PCB Printer
A	Electrolytic Capacitors	6.8	6.0	1.0	0.0	7.9
B	Copper inductors with ferrite or sintered iron cores	3.3	4.6	0.0	0.0	26.0
C	Plastic connectors	13.7	12.5	8.9	1.2	3.5
D	Metal parts	14.8	15.7	18.5	29.4	8.4
E	Quartz crystal	0.6	0.3	0.9	0.0	1.3
F	Plastic connectors with metal contacts	11.4	13.6	2.0	0.0	3.3
G	Multiple function integrated circuits	1.4	0.3	19.3	12.2	3.2
H	Semiconductor diodes					
I	Resistors			*		
J	Capacitors					

3.1.3 Comminution and stereoscopic analysis

Physical processing involved a grinding technique that used different equipment for the purpose of studying the behavior and the release of the materials. According to Guo et al. [15] the mill choice is fundamental for the release and physical separation of the circuit boards' components.

In order to increase the amount of liberated materials from the PCB, we used a grinding routine which included two types of mills the first of which, the blade mill, was used in order to reduce the particle size. Then the hammer mill, a device that performs pulverization by abrasion/friction between the particles and the hammers, facilitating the exposition and material liberation.

It should be mentioned that the printed circuit boards are polymeric and insulators, with one or more layers of copper, which allow for the electrical contact between electrical components (capacitors, resistors, diodes, transistors, magnetic components) used in electronic products [16]. The base can contain fiberglass, cellulose or both, denominated as FR-1 and FR-2 FR-4 or CEM-1 = respectively, these are just a few of the possible compositions.

Thus, during the comminution process performed on printed circuit boards by the release of fiberglass, an abrasive material which is released in the form of fine particles, such particles are lost mainly due to how they are fed in to the hammer mill. Despite the losses, studies [17,18] have shown that the processing of printed circuit boards using hammer mills is effective, since they represent the release of the metals present in PCBs. Beyond this, the study developed by Tavares [19] said that the release of the materials present on the PCB's present better results when compared with other comminution equipment such as the ball mill [19]. Figure 2 shows images captured with an optic stereo-microscope, in which the release of the materials and the exhibition of the metallic surface of the PCB's components can be seen.

3.1.4 Magnetic separation

Magnetic separation is used as selective method in finding the metals of interest. To study copper recovery or the recovery of expensive metals such as gold and silver, magnetic separation can be used for separating these metals in to non-magnetic parts. Table 2 presents the mass percentage of magnetic and non-magnetic parts of each of the models of the studied circuit boards. The lead free motherboards, video cards and the memory feature similar characteristics with non-magnetic parts ranging from 40% to 45% and from 55% to 60% in the magnetic parts. The Printer-PCBs demonstrated a reversed composition with almost 75% being made from non-magnetic parts, this mainly due to the large amount of copper present in their inductors. The motherboards manufactured prior to 2006 presented a number of metals with non-magnetic features close to 55%, higher than those boards fabricated more recently (Table 2).

3.1.5 Granulometric classification

The behavior of the motherboard, lead free motherboard and printer PCB samples were similar in terms of their granulometric distributions. For the three

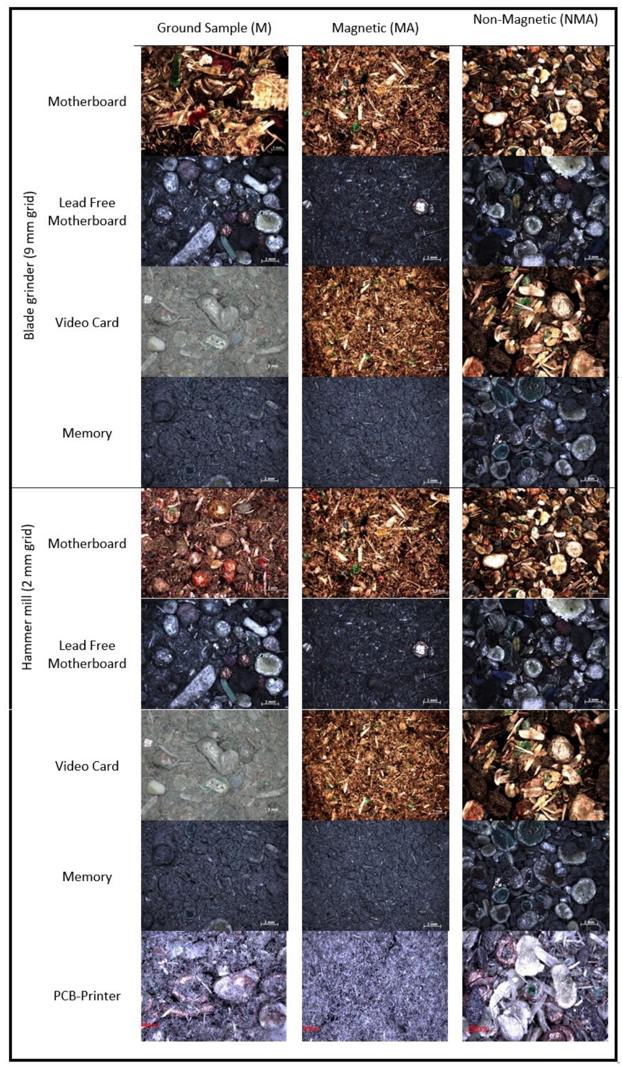

Figure 2. Images in binocular stereoscope during physical processing.

Table 2. Magnetic separation: comparison between different PCB's

Material	Mass percentage				
	Motherboard	**Lead free *motherboard***	**Video card**	**Memory**	**PCB Printer**
Non-magnetic	54.5	44.9	44.8	41.3	74.6
Magnetic	45.5	55.1	55.2	58.7	25.4

types of motherboard, the amount of material retained in the sieves with greater mesh widths (>0.5 mm) increased by more than 50% by weight, and approximately 52% for the motherboard to 59% for the lead free motherboard and 62% for the printer PCB .

The video card samples and PC memory exhibited behavior showing close and constant mass percentages throughout the granulometric parts with the exception of the parts <0,038 mm. Unlike other cards studied, in the video card and memory samples the highest percentage by mass of material was found in the smaller mesh sizes (< 0.5 mm):></ 0.5 mm):> 64% for video cards and 69% for printer PCBs.

In Figure 3 the granulometric analysis for ground printer board parts, lead free motherboards, video cards, memory cards and from the motherboard is shown.

Comparing the results with those found in the literature for PCBs from mobile handsets [20] and computer PCBs [21], it was seen that the behavior of the material is similar to that found in this study for motherboards, lead free motherboards and printer PCBs: where the trend is the accumulation of material on the thicker slices, even with different apertures having been used.

3.2 Characterization

3.2.1 Stereoscopic analysis: cross-section

Through Figure 4, which contains the images of the cross-section of all board models, it can be proven that they are of multi-layered type formed internally by interleaving layers of fiberglass with covers and externally by a resin surface. These can still be seen even in the memory cards that contain the greatest number of layers, possibly due to the large quantity of integrated circuits that are present relative to their small sizes. These integrated circuits have

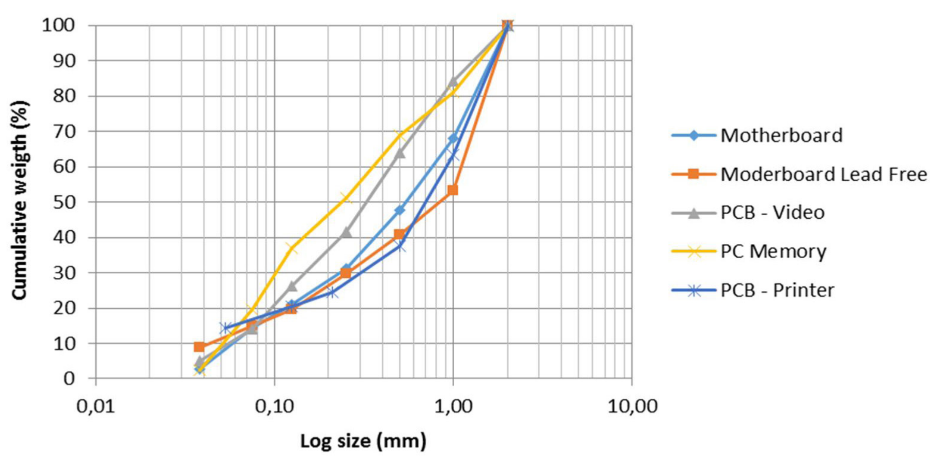

Figure 3. Granulometric classification.

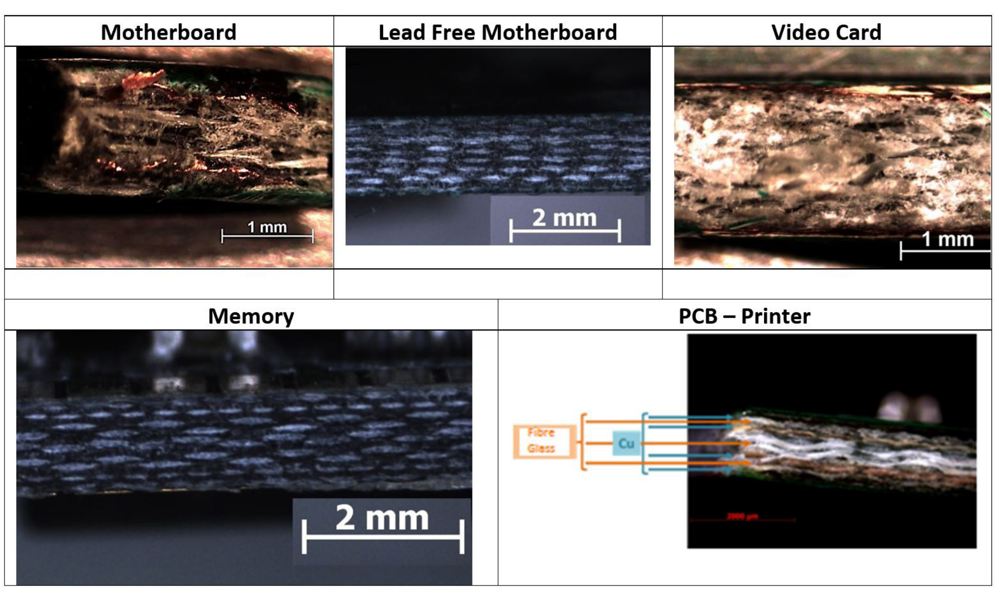

Figure 4. Magnifying glass.

hundreds of electrical contacts which make the use of multilayer boards necessary, on the other hand the video cards have a smaller number of layers, primarily due to their specific use, they don't require many integrated circuits.

3.2.2 Acid digestion, loss on ignition and mass balance

With the loss on ignition tests, it was possible to determine the amount of polymer and ceramic material present in each one of the printed circuit boards analyzed.

From the results obtained in the losson on ignition and acid digestion tests, percentage of metallic and ceramic, polymer parts were calculated using Equation 1 [22]:

$$Acid\ digestion = Minitial\text{-}\left(Pol + Me\right) \quad (1)$$

Where: *Me* is the amount of metal parts as a percentage by mass, result from acid digestion; *Pol* is the polymer fraction as a percentage by mass, result from loss on ignition tests; *Minitial* is the initial mass of PCB used; and the ceramic part is calculated by the difference between polymer and metal parts.

As noted in Figure 5, the printed circuit boards showed differences in their composition. For example for the printer, the lead free motherboard and the video card the material present in highest percentage was metallic, with percentages of 44, 43.7 and 35.8% respectively. The memory cards gave 24.6% of metal however the motherboards gave 35.8%, and for the motherboards the metallic material ranked second in quantity and the memory cards were in last place in this composition.

In Figure 5, it was found that the polymeric material on the motherboard was the most abundant, which corresponded to 38.3%. As for the lead free motherboard, memory card, the video card and the printer card, the polymer parts occupied the second position in the composition with percentages of 32, 30.5, 33 and 28.5% respectively.

However, we managed to determine that the ceramic material was the main material found on the memory card, with 45% of the mass being made of ceramic parts. In the remainder of the material we found ceramics in smaller amounts. The lead free motherboards presented 24.4%, 31.2% for the video cards, the printer cards had 27.5% and 25.9% for the motherboards.

The results obtained in this study are in agreement with other studies [7,23] found in the literature, in which heterogeneity and complexity has been reported in the composition of the printed circuit boards. In addition, factors such as the type of board, the function, the make and year of manufacture directly influence the concentration of materials present in PCB's [21].

Also found in the literature [24,25] that the composition of the materials present in the PCBs from the computers is: 40% metal, 30% ceramics and 30% polymer. These values are in accordance with those found in this work: 44% of metallic material, 28.5% of polymeric and 27.5% of ceramic.

3.2.3 Chemical analysis and aggregate value

Printed circuit boards had a metal quantity of approximately 30% by mass, which varied according to the type of equipment, manufacturing technology and

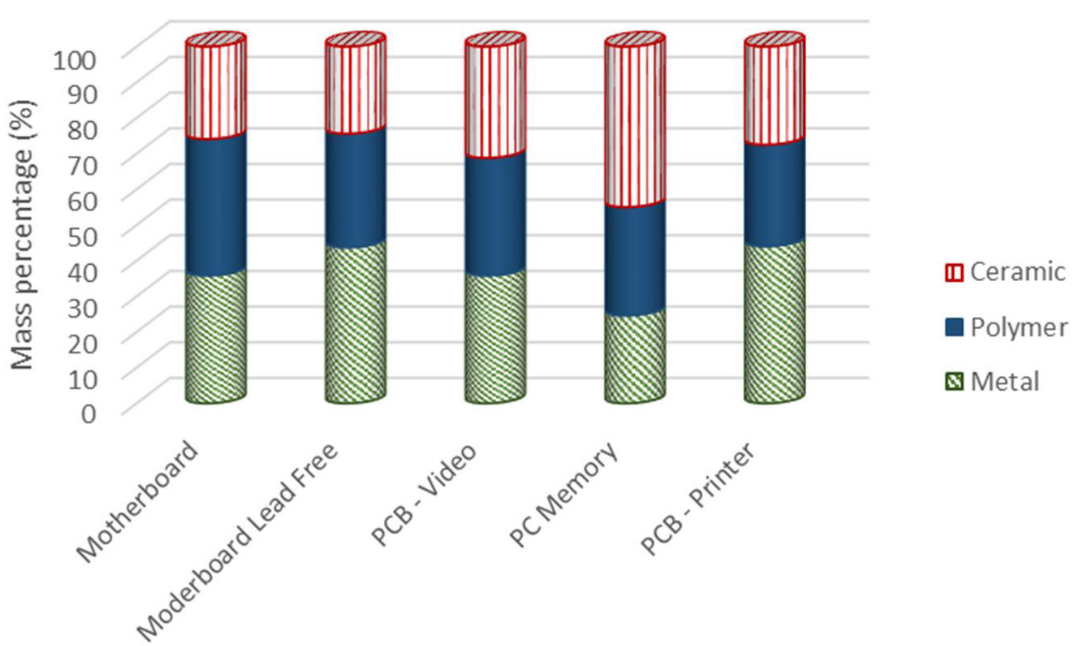

Figure 5. Mass balance of printed circuit boards examined in this study.

aggregate of components (resistors, capacitors, inductors, semiconductors and connectors) [7,8,26].

After chemical analysis of the acid digestion liqueurs, we calculated the percentage by mass of each metal present in printed circuit boards (Table 3).

The metals present in parts of the printed circuit boards can be divided into precious metals, base metals and toxic metals [27]. It was verified that the metal in the boards studied of the greatest concentration was Cu. This is because this is a PCB base metal and is also present in layers and not only on components. For all the samples studied the copper concentration was around 20% wt. with the exception of PCBs from printers that presented 32.5% wt. Cu in their compositions. This difference can be associated with the presence of Cu inductors, which have a mass percentage about 8 times larger than the motherboards and 6 times greater than lead free motherboards. Although the video cards and memory surveyed in this paper do not have copper inductors in their composition.

All other metals, with the exception of Fe and Al in the lead free motherboards, represent less than 5% by mass of the composition of the PCB.

As expected, there was variation in composition between the different types of boards studied in this work and this was also found in other studies (e.g. from mobile handsets [20] and computers [21,28]. The difference in concentration of the metals can be associated with the type of PCB studied, the methodologies applied in each work, the growing technological innovation [24,25], the origin of the materials used and the analytical methods [29].

Precious metals are the main market drivers for electronics recycling, followed by copper and zinc [9]. This is because the precious metals contained in printed circuit boards are less than 1% by mass of plate, however they can make up to 80% of the intrinsic value [30]. For this reason, there are numerous processes focused on the recovery of precious metals such as gold and silver [8]. Some techniques are: leaching with cyanide [11], nitric acid leaching [11], thiosulfate leaching [11,31,32], thiourea leaching [33] and bioleaching [21,29,34]. However, it is known that there is diversity in the composition of the PCBs depending on how they are used. Some boards may contain negligible amounts of precious metals or even not contain them at all. With the advancement of technology, the trend is the decline in the use of materials in the manufacture of boards with the same, or more, functions previously produced [7].

According to Institute for Scrap Recycling Industries, to transforming obsolete scrap into useful raw material is not only economically pivotal, but also is important to environmental protection, sustainability and resource conservation. The scrap recycling industry accounts for 0.62% of the EUA economic activity [35].

The materials recovery from WEEE result in several benefits when compared with primary raw materials as savings in energy, reductions in air and water pollution, reduction in water use and in mining wastes. The energy savings using recycled Al can reach 92%, 90% for Cu and 56% for steel [36].

After an extensive literature review of mobile phone recycling, Sarath et al. concluded that the recycling of WEEE is economically viable [37].

Assuming that in 1 t of printed circuit board a 100% of the Ag, Al, Au, Cu, Ni, Sn and Zn can be recovered, it has been estimated that the values of studied PCBs can reached at least US$ 6,000 until US$ 35,000, depending on PCB type, as shown in Table 4. It turns out that the average value that can be retrieved in a ton of printed circuit board is about 6 thousand dollars with the exception of PCB video and PC memory that have a value almost 2.5 and 6 times greater than for the other studied boards, respectively. This is because this type of boards has gold contacts all the way around its edges.

These values do not considering the costs of the process that may vary depending on the processing route chosen: physical/ mechanical, pyrometallurgical, hydrometallurgical, biohydrometallurgical or a combination of process.

Each route has advantages and disadvantages. Physical recycling is a technique that has low, or none,

Table 3. Characterization of PCBs: percentage of metals by mass

Material	Mass percentage				
	Motherboard	Lead free *motherboard*	Video card	Memory	PCB Printer
Ag	0,100	0,018	0,063	0,540	0,314
Al	4,000	5,700	1,236	2,382	3,730
Au	0,010	0,007	0,026	0,065	0,004
Cu	22,100	22,500	23,398	18,228	32,500
Fe	3,100	7,300	2,289	1,435	1,420
Ni	0,200	0,400	1,211	0,326	0,340
Pb	1,200	0,030	2,139	0,000	0,000
Sn	1,800	4,000	2,654	1,377	0,960
Zn	2,700	3,100	2,198	0,000	0,640
Outros	0,600	0,650	0,629	0,282	2,570
Total	35,810	43,705	35,842	24,635	42,478

Table 4. Values of metals recovered from a ton of printed circuit board

Metal	US$/t of metal	Motherboard		Leadfree Motherboard		PCB - Video		PC - Memory		PCB - printer	
		t metal per t of PCB	US$ in 1 t of PCB	t metal per t of PCB	US$ in 1 t of PCB	t metal per t of PCB	US$ in 1 t of PCB	t metal per t of PCB	US$ in 1 t of PCB	t metal per t of PCB	US$ in 1 t of PCB
Ag	575,142.57[1]	0.001	575.14	0.00018	103.53	0.001	362.99	0.0054	3,105.77	0.031	1,805.95
Al	1,969.00[2]	0.040	78.76	0.057	112.23	0.012	24.33	0.024	46.90	0.037	73.44
Au	46,810,361.70[1]	0.0001	4,681,04	0.00007	3,276.73	0.0003	12,376.42	0.0007	30,426.74	0.00004	1,872.41
Cu	6,767.00[2]	0.221	1,495.51	0.225	1,522.58	0.234	1,583.32	0.182	1,233.49	0.325	2,199.28
Ni	13,285.00[2]	0.002	26.57	0.004	53.14	0.012	160.91	0.003	43.31	0.003	45.17
Sn	21,075.00[2]	0.018	379.35	0.040	843.00	0.027	559.30	0.014	290.20	0.010	202.32
Zn	3,234.00[2]	0.027	87.32	0.031	100.25	0.022	71.08	0	0	0.006	20.70
Total			7,323.70		6,011.5		15,138.30		35,146.40		6,219.30

[1]London Bullion Market Association (LBMA) 06/04/2018 [38]; [2]London Metal Exchange (LME) 06/04/2018 [39]

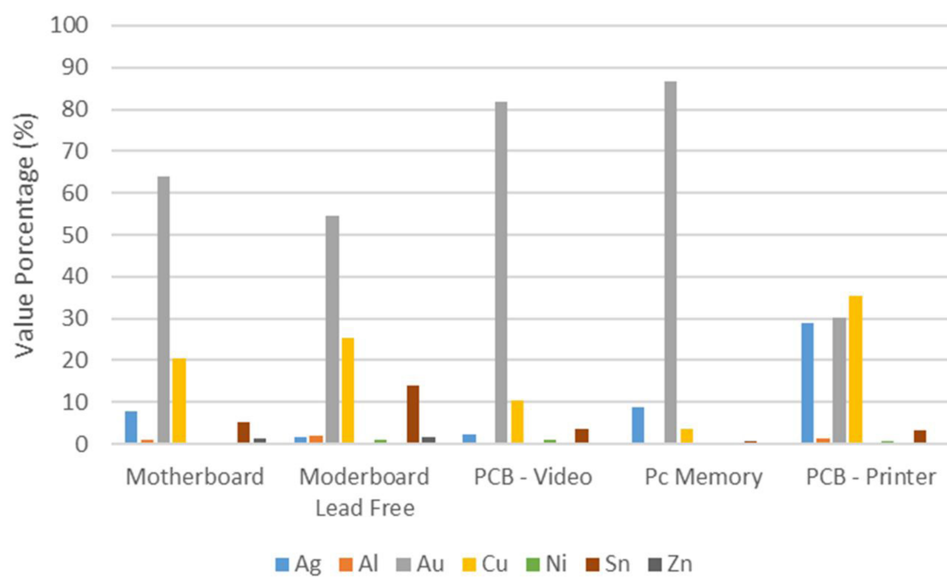

Figure 6. percentage of the value that each metal represents in relation to its mass percentage of composition of the PCB.

environmental pollution and the capex and opex is relatively low. However, the materials fractions separation process has to be enhanced to avoid the valuable metal losses (10-35%). Using pyrometallurgical techniques, it is possible to recover both non-ferrous and valuable metals. However, smelters have high capex and opex due to the intensive energy consumption and the need to treat toxic gases. Hydrometallurgical process is generally more selective than the above processes. The capex and opex is intermediary between physical and pyrometallurgical process. However, initial physical steps are used before leaching and purification techniques. PCBs that contain less than 100 g Au in a ton are considered low valuable wastes and cost-effective methods are required for the treatment of these wastes [40-42].

Considering the PCBs studied in this paper, just the types PCB – video and PC – Memory have more than 0.0001% Au in a ton. However, normally during WEEE industrial treatment the different PCBs types are mixed and the total Au content, as well as the sum of the other metals, make the process economically feasible.

In order to facilitate understanding of these results, the percentage of the value that each metal represented in relation to its mass percentage of and its composition of the PCBs was calculated (Figure 6).

As expected, gold is the metal with the highest value percentage against the concentration of which it is present in PCBs. Its market value is more than 45 million u.s. dollars per ton. The same conclusion was achieved by Tuncuk et al. after a literature review, as showed at Table 5 [41].

4 CONCLUSIONS

- The composition of the printed circuit boards studied varies between on board to another, with the metallic part being the main constituent of lead free motherboards,

Table 5. Percentage of metals by mass and percentage of the value that each metal represents in relation to its mass percentage of composition of the PCB. Adaptaded from Tuncuk et al. [41]

Type of e-waste	Content (% or g/ton) and contribution to economic potential (%) (in brackets)							
	Fe (%)	Cu (%)	Al (%)	Pb (%)	Sn (%)	Ni (%)	Au (g/ton)	Ag (g/ton)
PC boards	7	20	5	1.5	2.9	1	250	1000
	0	(10)	(1)	(0)	(4)	(1)	(64)	(5)
PC boards	2.1	18.5	1.3	2.7	4.9	0.4	86	694
	(1)	(10)	(0)	(0)	(7)	(1)	(26)	(4)
TV boardsa[1]	0.04	9.2	0.75	0.003	0.72	0.01	3	86
	(0)	(61)	(1)	(0)	(13)	(0)	(11)	(7)
TV boards	28	10	10	1	1.4	0.3	20	280
	(5)	(28)	(7)	(1)	(10)	(2)	(30)	(9)
Mobile phones	5	13	1	0.3	0.5	0.1	350	1380
	(0)	(5)	(0)	(0)	(0)	(0)	(67)	(6)
Typical ore grades	25	0.5	30	5	0.5	0.5	1	-

[1]Manufacturer waste without components.

video cards and printer cards, while the motherboards and memory cards feature the largest constituent polymeric and ceramic materials respectively;

- The release of the materials present in printed circuit boards depends on the grinding stage, in this study it was found that the grinding in a hammer mill of a mesh size of 2 mm and 1 mm released the materials present on the PCB's;
- Motherboard, lead free motherboard, and PCB from printer samples showed similar behavior in granulometric distribution with a tendency of material accumulation in the sieves with larger openings (>0.5 mm). whereas the video card and memory samples exhibited similar behaviorthough the highest percentage of material was retained in the smaller sieves (< 0.5 mm);
- The magnetic separation step should be avoided, especially for recovery of noble metals, due to drag loss;
- The memory cards feature the largest number of copper layers due primarily to their large quantity of integrated circuits;
- In all the studied boards the metal in greateest concentration is Cu ranging from 18 to 32.5% by mass;
- The average amount that can be recovered from a ton of printed circuit board is about 6 thousand dollars from motherboards, lead free motherboards and PCBs from printers. From video cards the value is around 15 thousand dollars and for memory the value is more than 35 thousand dollars; Silver, gold and copper are the metals with the highest value percentages;
- Considering the PCBs studied in this paper, just the types PCB – video and PC – Memory have more than 0.0001% Au in a ton. However, normally during WEEE industrial treatment the different PCBs types are mixed and the total Au content, as well as the sum of the other metals, make the process economically feasible.

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