Indicators for the Feasibility of WEEE Processing Plants in Brazil: a Relationship Between Virgin Mineral Copper Ore and the Recycling of Consumer Electronic Products

L.H.A. Cândido [a,b], W.K. Júnior [b], F. Palombini [b]

[a] ***candido@ufrgs.br***

[b] *Programa de Pós-Graduação em Design*

Universidade Federal do Rio Grande do Sul, Porto Alegre, Brasil

Abstract

This paper assesses the economic analysis of the implementation of WEEE – Waste Electrical and Electronic Equipment Directive – processing plants in Brazil, through the study of potential copper extraction from this secondary source. A comparative approach was performed on its copper grade related to levels of its virgin ore mineral extracted from mines located in Brazil, in the United States and through a global average. The results demonstrate that the amount of copper mass originated from the recycling of disassembly of twenty electronic products ranges from 0.24% to 17.83% of its total mass, with an average of 3.63% of copper. In eighteen of these products, values greater than 0.4% were found, which surpass current levels of copper in ore mines in the USA. In fourteen products, these rates exceed the index of 1.5% copper in the ore, considered the minimum rate for the feasibility of opening new units of copper underground mining in Brazil. Thus, this paper shows the economic analysis that aims to guide on the viability of deploying WEEE processing plants, focusing on the expansion of recycling and reuse of copper by the processing industry.

Keywords: WEEE; copper; recycling, environment.

1. INTRODUCTION

According to Alexander and Street [36], Patterson [31] and Radetzki [32], although copper content in the crust had been equivalent to 0.006%, it was the first used metal even before others that were more abundant, such as iron (6%) and aluminum (8%). Fingerl and Filho [11] while considering the demand of refined copper, which is around 11.8 million tonnes per year, state that global reserves would last for approximately 50 years. The minerals availability world scene, as well as and other natural resources, is of major importance for the sustainable development of the mining and the processing industries, nevertheless, according to Jenkins and Yakovleva [20], the world's leading mining industries have not yet adopted standard practices that address environmental and social issues. This leads the world consumption profile to look for alternatives in order to reuse the material.

The field of materials recycling permeates areas of both the extraction and the processing industry, however, it is possible to observe that the problem continues to grow, despite several technical and numerous researchers have already presented scientific solutions. Gordon [14] proposes that the reuse of copper already stored in tailings in the US would meet the national demand for copper over the following 9 years. Giurco and Petrie [12] raise the issue of the need for collaboration between network agents of the copper industry, proposing an integrated strategy for sustainable development of the mineral-to-metal-to-product value chain.

Other sources of copper can be discovered and appropriated in order to value the shortage of this metal. Agrawal and Sahu [4] state that effective recycling of metal rich scrap will be helpful by reducing the burden on primary resources, including the cost and energy consumption involved in this processing, as well as the spared of the disposal of hazardous parts, decreasing the environmental impact. However, in order to maintain effectively the use of copper by the industry, some key points should be considered such as facing the fact that mine is the weakest stage in the entire copper industry and hence governments should reinforce the practice of reuse of copper from wastes, compelling through rules and tax benefits (Guo and Song, [15]). Several other authors have studied the feasibility of recycling and applying secondary sources of important metals, such as copper, in the industry (Liu et al. [22], Padhan et al. [30] Matsumiya et al. [23], Nilanjana and Das [8], Djordjevic [9], Avettand-Fènoël et al. [6], and Zhou et al. [45]).

Gómez et al. [13] analyze the fact that even that the availability of old copper scrap has increased substantially over the past four decades, its recycling has not kept pace. The authors concluded that if copper scrap is not recycled soon after returning to the market, it would rarely be reused, assuming a higher cost as years go by. On the other hand, as the demand for copper resources continuous to increase, more copper will be recycled and the copper scrap market will become more important and valued, according to Aruga and Managi [5]. This emphasize the critical need to arrange units of copper recycling from waste, considering the environmental impact as well as the inherent benefits from such production system.

In this paper a historical overview of the consumption of primary and secondary copper profile in the world was performed. The direct impacts of the progressive generation of waste due to the low quality of the ore were highlighted, from 1900 to 2010. The relationship between increased consumption of copper with the consumer electronics industry was analyzed, as well as the possibility to take advantage of equipment for disposal for the extraction of copper. A practical verification of the potential of copper found in electronic products was raised in addition to the current deployment scenario of a dismantling center in Brazil.

2. WORLD COPPER PRODUCTION AND CONSUMPTION OVERVIEW

As discussed by some authors (Agrawal and Sahu, [4]; Kang and Schoenung, [21]; Vexler et al, [44]) copper has been widely used in the consumer electronics industry, due to its physical properties. Thus, in a period of 50 years, its annual consumption grew from 5 million to 19 million tonnes, according to the USGS - US Geological Survey ([42,43]).

Following the logic of increasing extraction, copper price was being raised to extraordinary levels and so a tonne of metal which was traded for approximately 700 USD, in 1960, has been increased to almost 9 000 USD, in 2011, according to the ICSG - International Copper Study Group [18]. According to Tanimoto et al. [37], in 2008, Brazilian copper production sector has generated 5 303 million USD in business, supporting over 18 000 jobs.

In Brazil, the increased copper consumption impact in home appliances can be evaluated after the standardization of plugs and sockets determined by NBR 14136:2012, published by ABNT (Brazilian Association of Technical Standards) [3]. This standard, according to ABNT, sets the dimensions of plugs and sockets characteristically nominated up to 20 A/250 V, for household and similar purposes, for connection to electric distribution systems with rated voltages from 100 V to 250 V. As the determined standard requires the use of grounding, with the addition of the neutral conductor, copper consumption has automatically increased at the range of 50%, because previously it had only the requirement of the 2 phase conductors. Certainly, the impact on the extraction and marketing of copper will be strongly influenced by it.

Evaluating copper consumption increase in Brazil it can be noticed that even with a growth in secondary copper production, there is also a raise of its imports and exports (MME, [25]). Primary copper is considered the one that is extracted directly from the ore, along with secondary copper as the one resulted from a recycling process (ICSG, [18]).

As shown by several authors (ICSG, [18]; Meadows et al., [24]; Mudd, [26]; Norgate, Jahanshahi and Rankin, [28]; Schodde, [33]; US Bureau of Mines, [41]), analyzing data from the global extraction of this metal, since 1900, it is possible to draw a comparison between global copper grade, i.e. the average concentration of copper in the ore, and the amount of residues generated during this process. Thus, Figure 1 shows the amount of Residues Generated (RG) per tonne of extracted copper, its relationship to global Copper Grade (CG), as well as the amount of Primary Copper (PC) produced globally and the production of Secondary Copper (SC), through the years 1900 to 2013.

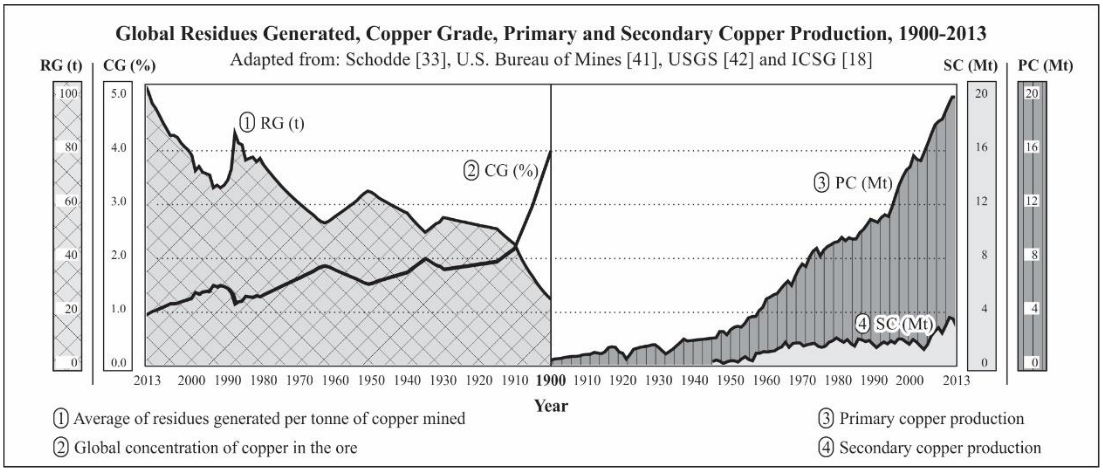

Figure 1: Historical global tendencies on copper quality – 1900-2013.

As the average global Copper Grade (*CG*) consist of a percentage level relative to the amount of primary Copper content (*Cu*) extracted from its ore, through mining, it is possible to estimate the volume of Residues Generated (*RG*) during this process, as shown in Eq. 1.

$$\frac{RG_i}{Cu_i} = \frac{100}{CG_i} \quad (1)$$

Since the extraction of 1 average tonne of Copper from mining during an specific time (tCu_i), through Eq. 1 the amount of Residues Generated (RG_i) can be obtained by inverting the percentage index of copper grade (*CG*) relative to its specific period or year (y_a - y_b), observed in Eq. 2.

$$RG_y = \frac{100 \times Cu_y}{CG_y} \Rightarrow RG_y = \sum_{i=y_a}^{y_b} \frac{100 \times Cu_i}{CG_i} \quad (2)$$

While considering the global production of approximately 83 Mt of primary copper (ICSG, [18]), during the years of 2009-2013, as well as its concentration in the ore (Schodde, [33]), using Eq. 2 it may be calculated the amount of waste generated (W) during this mining process. Thus, during the analyzed period of 5 years of global copper mining, it had been produced over 8.2 billion tonnes of residues worldwide. When analyzing global CG (as seen on Fig. 1), which in 1900 was approximately 4.0%, there was a quite accentuated decline, reaching approximately 0.95% by the year of 2013. As shown by Fan et al. [10], the copper concentration in producing countries ranges from 0.24% to 3.78% and according to Schodde [33] and Mudd [26], the current global estimative of CG lies about 1%.

Therefore, it is clear that in order to maintain the amount levels of primary copper presently used it will be generated a larger volume of waste, and hence, as pointed out by Hatcher, Ijomah and Windmill [16]; Meadows et al. [24]; Norgate and Jahanshahi [27]; Northey, Haque and Mudd [29], it will be noticed an increase in the energy consumption required for the process of extraction and refining of this material. It is noteworthy that according to data presented by IPEA [19] the Brazilian mining industry generated, in 1996, approximately 202 million tonnes of waste and the projection for 2030 reaches levels of 684 million tonnes.

Evaluating the data presented in Figure 1, concerning the reduce of the CG rate, it can be emphasize a tendency to increased costs for extraction and refining of virgin metal for years to come. Thus, as noted by Guo and Song [15] and Terazono et al. [38], the rapid growth of global demand for copper will accelerate the depletion of natural resources in the primary layers of the Earth and hereafter it is going to be necessary to dig deeper and to use more energy in this process, generating a higher volume of residues. Consequently, copper dependent industries will tend to feel the impact over this increasingly rare and expensive raw material.

According to data from Standard CIB Global Research [35], 42% of worldwide produced copper is used in the consumer electronics industry, with construction consuming 28% and transport, 12%. Among various consumer countries China is responsible for the usage of 43% of the world's copper (ICSG, [18]), and represents 15.33% of its global production (UNIDO, [40]). This corresponds to a 2.7 million tonnes of copper usage in the consumer goods, machinery and electronics industries (Castro and Sánchez, [7]; Shang et al., [34]). Thus, it can be stated that those industries have a high potential use of recycled copper. Still, there is a clear need for studies to evaluate the affordability of creating and/or expanding profitable recycling centers for consumer electronics products.

In this recycling prospectus, reuse of copper gained prominence over other materials. Many countries have already opted to use imported copper derived from discarded consumer electronic products as a way to insure themselves against future shortages of metal (ICSG, [18]). It is estimated that, on 2013, from the 20.1 million tonnes of copper produced in the world, 3.6 million tonnes were derived from recycled material, corresponding to 17.9% of the whole production (ICSG, [18]). In assessing this information, it can be concluded that by using only 17.9% of recycled copper, there is a real possibility of expanding its use at much higher levels.

According to a report released by the United Nations Environment Programme (UNEP, [39]), poor organization of electronics collection and disassembly sector in Brazil gives the country a high potential to receive and adapt technologies to deploy an recovery industry for materials and metals that compose such equipment.

3. MATERIALS AND METHODS

In order to indicate a relationship between the CG level as well as the rate of copper originated from consumer electronic products, twenty of this products were disassembled (Table 1) through a manual process, utilizing tools as pliers e screwdrivers. These products would have been destined to disposal due to malfunctioning or obsolescence. All selected products are electronic-based and consequently powered by electrical current through the usage of conductive materials, such as copper. Thus, these principals became a parameter for the selection of products for disassembly, which was reinforced by the chart of most commonly found home appliances in Brazil, presented by ABINEE [2] and IBGE [17]. The focus of this procedure was to evaluate components containing wires and sheets of copper, as well as its specific copper grade related to each total mass.

Table 1: Copper grade on evaluated consumer electronic products.

Product		Total mass (g)	Copper mass after disassembly (g)	Copper grade (%)
A	Washing machine timer	380	20.3	5.34
B	Car CD Player	1 302	3.9	0.30
C	Compact Stereo	2 718	17.3	0.64
D	Drill	1 475	60.6	4.11
E	Electric shower head	485	27.4	5.65
F	Epilator	430	6.8	1.58
G	Hair dryer	405	27.4	6.77
H	Hair iron	540	16.0	2.96
I	Toaster	1 492	13.6	0.91
J	Clock Radio	496	18.3	3.69
K	Portable audio cassette players (1)	140	2.5	1.79
L	Portable audio cassette players (2)	179	2.1	1.17
M	DVD player	1 854	12.1	0.65
N	Videocassette recorder	6 150	14.6	0.24
O	Notebook (1)	2 300	410.0	17.83
P	Notebook (2)	3 280	187.0	5.70
Q	Bluetooth wireless headset	79	6.9	8.73
R	Circuit breaker	820	17.5	2.13
S	Contactor	1 160	72.0	6.21
T	Windscreen wiper motor	822	25.9	3.15
Total		**26 507**	**962.2**	**3.63**

Over a total amount of 26.507 kg of several disassembled electrical appliances, it was obtained 0.9622 kg of copper, which corresponds to 3.63% of the total mass of the equipment. Aiming to relate these values with the data on the extraction of copper, Figure 2 shows the relationship between products disassembled on Table 1, USA copper grade of 0.4% (Meadows et al., [24]), Brazil CG ranging from 0.7% to 2.5 % (Fingerl and Son, [11]; Tanimoto et al., [37]) and the average global CG of 1%, as shown in Figure 1.

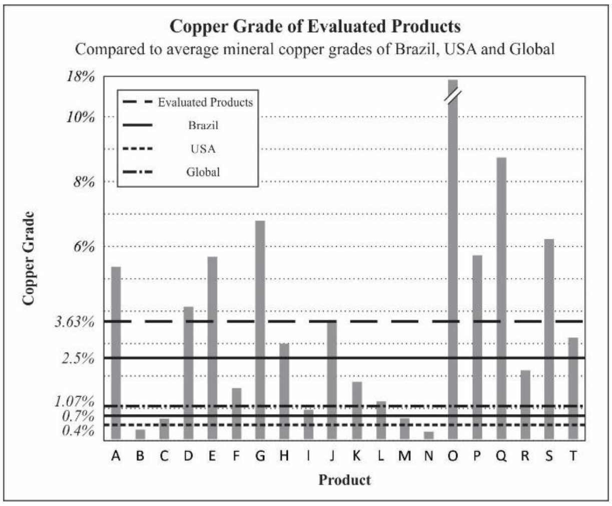

Figure 2: Analysis of the copper grade of evaluated products compared to primary copper production grades in Brazil, USA and Global.

The compared CG correspond to the average quality of primary copper extracted from ores. Thus, it is possible to verify that the average amount of copper that can be obtained during disassembly of consumer electronic goods exceeds the major referenced copper grades, which indicate the current quality of copper ore in Brazil, USA and Global.

When evaluating the data presented in Figure 2, it can be observed that only the products B (car CD player) and N (videocassette recorder) stayed below the 0.4% copper grade, contained in virgin ore in the USA. The analyzed data demonstrates that the copper recycling rate varies from 0.24% to 17.83%. At eighteen disassembled products, corresponding to 90%, copper percentage was higher than 0.4%, which outweigh the current levels of ore mines quality in the USA. In fifteen products, i.e. 75%, the rate of copper exceeds the global index estimated of 1%. It can be noticed that, according Fingerl and Filho [11], the economic viability for the foundation of new protected underground ore mines in Brazil normally must present levels above 1.5% CG, a percentage that is surpassed in 70% of analyzed products.

In this analysis, it was verified that the average of this percentage exceeds the amounts of copper found in the ore, regardless of its origin. At the current level of extraction of such metal, more waste is being generated every year, increasing the environmental impact. Thus, if the copper used by the processing industries were obtained from alternative sources such as, for example, recycling of electronics products, millions of tonnes of waste would be spared.

In this sense, aiming to relate the volume of electrical appliances produced in Brazil between 2005 and 2013 (ABINEE, [2] and IBGE, [17]) with the expected volume of Residues spared (Rs) from being extracted, Table 2 projects the total Rs that would be prevented in Brazil, if the copper of such products was recycled. It is emphasized that the world copper grade of 1% is considered for the calculation of Rs.

Table 2: Copper grade on evaluated consumer electronic products.

Product	Area	Households in Brazil (millions of units)	Source	Copper volume (g)	Total copper volume	Residues spared (Rs)
A	Home appliances	143	ABINEE, [2]	20.3	2 903	287 387
B		179		3.9	30 967	3 065 733
C				17.3		
D				60.6		
E				27.4		
F				6.8		
G				27.4		
H				16.0		
I				13.6		
J		251		18.3	4 593	454 737
K				2.5	628	62 123
L				2.1	527	52 183
M		40	IBGE, [17]	12.1	484	47 916
N				14.6	584	57 816
O	Computer equipment	219	ABINEE, [2]	410.0	89 790	8 889 210
P				187.0	40 953	4 054 347
Q		-		6.9	-	
R		-		17.5	-	
S	Electrical materials	-		17.4	-	
T		-		25.9	-	
Total				**962.2**	**171 429**	**16 971 451**

The results presented in terms of environmental impact of Rs demonstrate that the global practice of recycling of electrical appliances can sustain the life of copper mines. This does not mean, however, that the extraction of copper should be interrupted, but its speed could be slowed down to less impact levels.

Determining the average amount of copper present in several consumer electronics products as well as their potential impact to reduce the disposal of waste derived from mining demonstrate the environmental benefits of such practice. Nevertheless, in order to be fully implemented the mass recycling of Waste Electrical and Electronic Equipment (WEEE) need to be analyzed over the economic point of view of the process.

4. EVALUATION OF FEASIBILITY OF WEEE PROCESSING PLANTS IN BRAZIL

In addition to the copper grade in electronic products, through the relation of its total mass compared to quality rates found in Brazilian, American and global ore mines, it can be made an estimated cost of mass disassembly. When implementing WEEE processing plants, several expenses are taken into account, related to its capital expenditure (CAPEX) and operational expenditure (OPEX), as well as the disassembly level for obtaining a profitable amount of copper.

Considering an annual processing capacity of 1 200 tonnes, according to the Brazilian Agency for Industrial Development (ABDI, [1]) an initial investment of BRL 35 600.00 is required. Such capital expenditure (CAPEX) includes the purchase of equipment as 01 palletizer, 05 human-powered vehicles, office furniture, 02 weighing scales and 06 transport containers. As for the costs related to the operational expenditure (OPEX), it includes employees' salaries and taxes, warehouse rent, personal protective equipment and others, for a total monthly of BRL 9 760.00.

As discussed before, referring to the average copper grade of consumer electronic products being as high as 3.63%, it necessary to assure such level of disassembly. In order to make WEEE profitable, a high level of dismounting is required; therefore, at least 96.4% of each electronic product processed by the plant should be detached. The calculation of the Recycling Expenditure (*RECPEX*) index that relates the disassembly grade (*DG*) for each tonne of WEEE (t_{WEEE}) can be seen on Eq.3 (ABDI, [1]):

$$RECPEX = 0.280 \times e^{7.547 \times DG} \times t_{WEEE} \quad (3)$$

Using Eq. 3 it is possible to determine the Recycling Expenditure for a 96.4% Disassembly Degree of BRL 392.35 per tonne. As the analyzed processing plant has a monthly capacity of 100 tonnes, the RECPEX reaches BRL 39 235.00. Such expenses are enough to ensure the sustainable development on evaluated WEEE processing plant. However, in order to make it profitable, the economic analysis should also consider the incomes generated through the extraction of secondary copper.

As seen on Table 1, an average tonne of WEEE contains about 3.63% of copper, or 36.3 Kg. With a monthly processing of 100 tonnes, there is about 3.630 t of the metal, which could be sold up to USD 7 000/t (ICSG, [18]), over BRL 15 500/t. Aiming to summarize the economic analysis of an 1 200 t annual capacity WEEE processing plant, Table 3 presents the return on investment forecast for 6 months.

Table 3: Economic Analysis of a WEEE Processing Plant, in Brazilian Real (BRL).

Month	1	2	3	4	5	6
CAPEX	- 35 600.00	- 35 600.00	- 35 600.00	- 35 600.00	- 35 600.00	- 35 600.00
OPEX	- 9 760.00	- 19 520.00	- 29 280.00	- 39 040.00	- 48 800.00	- 58 560.00
RECPEX	- 39 235.00	- 78 470.00	- 117 705.00	- 156 940.00	- 196 175.00	- 235 410.00
Incomes	58 067.68	116 135.36	174 203.04	232 270.72	290 338.40	348 406.08
R TOTAL	**- 26 527.32**	**- 17 454.64**	**- 8 381.96**	**690.72**	**9 763.40**	**18 836.08**

The running total on the economic analysis shows that from the fourth month forward, the processing plant starts to return the investment, with a Running Total of BRL 690. On the sixth month, there is a return of almost BRL 19 000, demonstrating that half of the CAPEX could be returned during this period. According to Table 3, it may be seen that the investment on a WEEE processing plant can be profitable. The great amount of WEEE being disposed every day should be seen as an indicator for the institutional promotion of processing plants.

This factor can be set by the consumption level of electronic products in each country; i.e. countries that are highly consumer of electronics can support the implementation of processing plants and recycling of copper. These actions would result on the deceleration of extraction of virgin copper in each country as well as on independence from the importing of such metal. The deployment decision can be set by the amount of electronic products disposed passible to be disassembled and their geographical distribution in the country. These factors can be seen as long-term economic incentives since increasing the amount of recycling can lead directly to a decrease on the extraction of primary copper, resulting on more sustainable copper mines.

5. CONCLUSIONS

When considering the data presented throughout this research it is clear that while reducing the copper grade, its extraction at a global level become more expensive every year, generating larger amounts of residues and increasing the environmental impact for its mining. By highlighting the increased use of copper from a secondary source, it is possible to infer that this trend should continue in the coming years. The data show that this fact is mainly due to the scarcity of this primary source for economic extraction levels in the crust of the Earth. Reversing this situation is practically impossible since the ore supplier layer cannot be recovered. Therefore, deeper layers are being extracted, further raising the level of waste generated and especially without a suitable destination.

This research shows that between twenty disassembled electrical appliances fifteen of them have the potential for reuse of copper, which is above the world average of 1% copper contained in virgin ore as well as 0.4% rate of copper obtained in mines in the USA. The study demonstrate an average 3.63% copper grade in WEEE, which may be stated that consumer electronic products currently have a higher exploration potential compared to regular copper ores, with the advantage of being able to be generated everywhere.

The possibility of establishing of WEEE processing plants through an economic analysis was performed, considering the expenses related to capital, operational and recycling expenditures. It was seen that a 1 200 t annual processing plant could have half of its investments returned in six months, further creating employments and recovering electronic residues that would be disposed on the environment.

The process of obtaining copper through its secondary source, such as electronic equipment is demonstrated to be not only environmentally beneficial but also economic profitable. Recycling copper from an electronic residue source can be easily implemented, requiring few equipment and investment; it should not be seen as a way to end primary metal extraction, but an approach to lengthen the life of mines, ensuring to be healthier extracted for longer times.

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