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Economic and environmental assessment of recycling and reuse of electronic waste: Multiple case studies in Brazil and Switzerland

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ABSTRACT

The increasing quantity of electronic waste is a societal problem due to the imminent risk of eco-system contamination from harmful substances present in these products. Therefore, recycling and reusing these materials could mitigate environmental impacts and provide economic gains. The present research is aimed at assessing the economic and environmental advantages of adopting Waste Electrical and Electronic Equipment (WEEE) reverse logistics for recycling and reuse by three Brazilian manufacturers of electro-electronic products,and three recyclers,two located in Brazil and one located in Switzerland. Specifically, this study maps the processes used by three recyclers. These multiple case studies incorporated both observation and semi-structured interview. The Mass Intensity Factor was used for the environmental impact assessment. We found that the adoption of electronic waste reverse logistics for recycling and reuse resulted in reduction of the environmental impact in the abiotic, biotic, water and air compartments and economic gains for the manufactures and recyclers, indicating a promising market in the Brazil. Another relevant result was the presentation of a simple eco-efficiency tool to be used in organizational practice. This tool provides a performance indicator based on indexes to implement goals for continuous recycling and reuse improvements, aimed at achieving a closed cycle. However, electronic waste recycling and reuse processes in Brazil are decentralized and, therefore, the development of a cooperation network as a whole is complex. Furthermore, precious metal recovery from printed circuit boards is a process carried out specifically by foreign enterprises because the Brazilian manufacturers and recyclers do not have enough technology due the lack of resources for investment. Thus, the Brazilian government has been holding meetings with the manufacturers and recyclers to develop a sectoral agreement in order to support financially the transfer of this technology for recycling of printed circuit boards to Brazil. In addition, this fact contributes to the National Solid Waste Policy, and it increases the financial profitability of Brazilian recyclers because with this process the recyclers could extract precious metals for sale increasing the economic gain.

1. Introduction

The worldwide growth in industrialization and increasing competitiveness have resulted in an increased production of electronic products in various markets. Following this growth, electronic waste has become a significant problem, particularly in the context of the environment. However, electric and electronic waste disposal may present commercial opportunities, because they contain precious metals, such as gold, aluminium, copper, silver, and bronze, among other viable alternatives (ABDI, 2012). Electronic waste also includes components such as polymers (plastics), glass, gold, copper, and silver (Widmer et al., 2005). Nevertheless, the printed circuit board (PCB) is considered to be the main component found in electronic waste (Ladou and Lovegrove, 2008).

Waste electrical and electronic equipment (WEEE) has a broad relationship with discarded household appliances and other electrical appliances. In the electronic waste sector, WEEE also describes informatics items, such as computers and other peripherals (Robinson, 2009). There is a close relationship between the two applications of the term, considering that a great deal of household appliances and vehicles are equipped with PCBs, LCD monitors, and AC/DC adaptors or batteries (Kholer and Erdmann, 2004).

Thus, it is important to adopt reverse logistics for WEEE recycling and reuse (Achillas et al., 2012; Ayvaz et al., 2015). Reverse logistics consists of planning, implementing, and controlling the processes of raw materials, and of finished, rejected, and discarded products, returning these to the manufacturing cycle in an environmentally correct manner, grounded in legal terms, and with the least environmental impact possible (Rogers and Tibben-Lembke, 1998). Law 12.305 defines reverse logistics as a business strategy aligned with the

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requirements of the Brazilian National Policy on Solid Waste (NSWP) to reduce the environmental impact of waste, and is aimed at promoting actions to ensure that the flow of solid waste is directed back into the production chain, or chains. It is an economic and social development tool that facilitates the collection and restitution of solid waste back to its producers, so that it can be treated or re-employed, either as new products within the same cycle, or in other production cycles; in this way, it does not generate waste (Brasil, 2010). Agrawal et al. (2015) mention that the main WEEE reverse logistics process includes product acquisition, collection, and inspection/sorting, as well as recycling and reuse or final disposal, because these offer the opportunity for economic gain. In addition, according to Dixita and Badgaiyanba, (2016), it is important to adopt WEEE reverse logistics to reduce the environmental impact of waste, and to reduce the improper disposal of e-waste.

Recycling is a set of techniques aimed at removing the most valuable waste and reusing it in the production cycle, either in the original or in a parallel production cycle. The recycling process starts when discarded products are disassembled and their parts are sorted according to material categories (Thierry et al., 1995; Ladou and Lovegrove, 2008; Ravi, 2011). The aim is for these parts to be turned into feed material or new products (Brasil, 2010). WEEE recycling processes are an attractive business niche, for both electronic product manufacturers and other product components. The recycling of PCBs constitutes a relatively new opportunity in Brazil, with potential growth in this field related to the extraction and reuse of precious metals (Castro and Martins, 2010). This methodology has only been investigated in the Macedonia region of Greece. Achillas et al. (2010b) present diverse treatment practices related to electro-electronic waste after their disposal and subsequent waste stream, but do not address separation, reuse, and recycling. Thus, we conducted six interviews and observations, mapping WEEE reverse logistics for recycling and reuse processes in Brazil. This presents the main barrier to manufacturers of electro-electronic products and Brazilian recyclers adopting WEEE reverse logistics, as well as developing a closed cycle in Brazil. Therefore, this work makes a significant contribution to the scientific literature and organizational practice.

A systematic literature review of economic and environmental assessments of the adoption of WEEE reverse logistics follows. Studies on environmental gain in Brazil use mathematical modelling tools and qualitative data, aiming to encourage the NSWP to reduce pollution (Bouzon et al., 2016; Souza et al., 2016; Guarnieri et al., 2016) and to increase the number of recyclers with technological capabilities (Souza et al., 2016; Ghisolf et al., 2016; Caiado et al., 2017; Foelster et al., 2016; Bouzon et al., 2016). Other studies have estimated feasible locations using mathematical modelling tools for WEEE collection and shipment to recyclers, resulting in environmental gains in Greece (Achillas et al., 2010a,b, 2012). In Turkey, linear programming has been used to prevent the disposal of WEEE in landfills (Kilic et al., 2014; Aras et al., 2015). Several studies have presented qualitative findings on the environmental gains of implementing reverse logistics, indicating the important development of government laws for WEEE reverse logistics in Texas for the disposal of WEEE (Assavapokee and Wongthatsanekorn, 2012). In China, there is no control on WEEE reverse logistics, which has resulted in negative environmental impacts (Lau and Wang, 2009; Liu et al., 2016) and little motivation for new recyclers (Li and Tee, 2012). In Germany, researchers have used mathematical modelling to optimize 50% of the emissions of CO_2 in the transport process (Walther and Spengler, 2005). However, no scientific research studies have established how to minimize the environmental impact on abiotic, biotic, air, and water compartments by adopting WEEE reverse logistics, particularly in Brazil. Thus, this study contributes to the literature and to organizational practice.

Several studies have examined the economic advantages of WEEE recycling and reuse using virtual simulations and mathematical methods. For example, Agrawal et al. (2015) showing the cost reductions compared to logistics process optimization and fuel economy using a linear programming model (Walther and Spengler, 2005; Achilles et al., 2010a,b, 2012Achilles et al., 2010a,b, 2012Achilles et al., 2010a,b, 2012). The application of mathematical simulations has also demonstrated the reduction in electronic waste disposed of in landfills (Aras et al., 2015). Then, studies have developed virtual simulations for the reverse production system infrastructure design of electronic products in Texas in the United States (Assavapokee et al., 2012). In addition, stochastic programming has been used to minimize pollution in Turkey (Ayvaz et al., 2015). In Brazil, there is uncertainty related to the investment in international technology transfers for recycling (Bouzon et al., 2016; Araujo et al., 2015). Thus, it is important that the government provide fiscal incentives to implement new recyclers and collection points to increase the economic gain from the reuse of WEEE (Souza et al., 2016; Guarnieri et al., 2016; Caiado et al., 2017). Therefore, cost analyses are not easy to implement in practice (Agrawal et al., 2015)

However, no studies have computed the cost reductions, or returns on investments, from adopting WEEE reverse logistics in Brazil; the only estimates are provided through mathematical simulations. Gu et al. (2016) mention the lack of research providing cost analyses of the adoption of WEEE reverse logistics in organizations, which are important to motivate the adoption of recycling and reuse to exploit the opportunity for economic gain. In addition, after conducting the environmental and economics assessment, this study presents two indices to help industry managers in their decision-making processes. The economic advantage index (EAI) and environmental gain index (EGI) can be used as performance indicators for manufacturers of electro-electronic products and WEEE recyclers in order to improve recycling and reuse in a closed cycle. The indices presented in this paper contribute to both the scientific literature and to organizational practice. They are an innovation for managers in terms of performing economic and environmental assessments, and are easy to apply. Managers and researchers need eco-efficiency tools that are simple, rather than complex.

Therefore, based on the research gaps described above, the following research questions were formulated. Does the adoption of WEEE reverse logistics by three manufacturers of electro-electronic products in Brazil for the recycling and reuse of waste reduce its environmental impact and provide economic advantages for these manufacturers?

The present work aims to assess the economic and environmental advantages of adopting WEEE reverse logistics for recycling and reuse by three manufacturers of electro-electronic products, located in Sao Paulo City, Brazil, and three recyclers, two located in Sao Paulo City, Brazil and one located in Switzerland. Specifically, mapping and describing the WEEE recycling processes was used to determine if Brazil has the technology necessary for recycling PCB to reuse precious substances.

The article is structured as follows. Section 2 presents a literature review of WEEE Reverse Logistics; Section 3 presents the methodology; Section 4 presents a multiple case study; Section 5 provides the discussion and Section 6 the conclusion.

2. Economic and environmental advantages of adopting WEEE reverse logistics for recycling and reuse

Research shows that manufacturers of electro-electronic products and recyclers reduce the environmental impact of their products by adopting WEEE reverse logistics. In studies based on Brazil, Araujo et al. (2015) utilized RFID for waste management in order to minimize pollution. Guarnieri et al. (2016) mention that encouraging the adoption of WEEE reverse logistics should include providing environmental education in schools, companies, and commerce on the NSWP, as well as stimulating partnerships between the government and companies. Souza et al. (2016) concluded that the development of the NSWP was important for the implementation of the formal recycler. However, Bouzon et al. (2016) found that companies and recyclers do not follow the environmental regulations in Brazil. Ghisolf et al. (2016) use mathematical modelling to predict that the implementation of new recyclers will take more than 20 years. These findings suggest that the government should provide fiscal incentives for structuring. Nevertheless, Foelster et al. (2016) used a life cycle assessment to show that the recycling of 1000 refrigerators reduced emissions by 720 kg of CO_2, and Caiado et al. (2017) discuss buying carbon credits to avoid the environmental costs associated with the inadequate disposal of WEEE.

Achillas et al. (2010a,b) used a decision support system to show the optimal location for electrical and electronic waste treatment plants to reduce inadequate WEEE disposal in Greece. Achillas et al. (2012) indicated that optimizing their recycling processes using reverse logistics may, in turn, lead to a net fossil fuel reduction. For instance, in Macedonia, Greece, there has been an approximate 5% reduction in CO_2 pollutants to the Earth's atmosphere. The application of simulation models in solving stochastic programming problems demonstrates that it is possible to reduce air and environmental pollution in Turkey (Ayvaz et al., 2015). Other research in Turkey on recycling units in Ankara, Istanbul, and Izmir uses mathematical simulations to show that the environmental impact may be reduced by minimizing electronic waste in landfills (Aras et al., 2015). These simulations provide optimum locations of storage sites and recycling facilities for each scenario, satisfying the minimum recycling rates stated by the European Union directive for each product category (Kilic et al., 2014).

From the same environmental perspective, the absence of federal regulations does not prevent electronic waste from going to landfills and waste treatment plants in Texas, United States. This is a problem, if not dealt with as a priority, and may cause severe damage to the environment in the long term (Assavapokee et al., 2012). Thus, communities in Texas should be encouraged to dispose of WEEE correctly (Kochan et al., 2015).

The lack of control over China's electronic waste recycling in informal and formal sectors, the increase in electronic equipment production, and the volume of waste being generated cause severe risks for contamination of the environment and the population (Liu et al., 2016). The operation of formal and informal recyclers reduces WEEE and the emissions of pollution (Li and Tee, 2012), corroborating the need for Chinese environmental laws on the adoption of WEEE reverse logistics (Lau and Wang, 2009).

Walther and Spengler (2005) discuss the opportunity of reducing the transport costs for the collection of WEEE in Germany by 50%, thus reducing emissions of CO_2. Therefore, based on existing scientific publications focused on the environment, there are negative qualitative consequences from using fossil fuels and having electronic waste discarded in landfills. However, quantitative studies focus primarily on the reduction of CO_2 from pollutants, using virtual scenarios and mathematical simulations. Environmental impact assessments on biotic, abiotic, air, and water compartments are still lacking. Moreover, no studies present a complete mass balance of the chemical components contained in WEEE, especially the waste extracted from PCBs. Thus, the environmental impact assessment presented here provides indices (performance indicators) for the practical implementation of WEEE recycling. These environmental indices can be used to complement other performance indicators to promote management within the company and the dissemination of green marketing to customers, suppliers, and shareholders.

Additionally, the adoption of WEEE reverse logistics by manufacturers of electro-electronic products should provide an economic advantage by using recycling, reuse, and sales of materials. Brazilian shareholders are uncertain over the investment in international technologies for the recycling of WEEE (Bouzon et al., 2016). This result agrees with that of a study based on China (Lau and Wang, 2009). Moreover, it is necessary to invest in collection points that provide easy access and that boost partnerships with recyclers of WEEE in Rio de Janeiro to develop the economy of this segment (Souza et al., 2016). The investment in RFID for waste management has resulted in financial gain (Araujo et al., 2015). This suggests that fiscal incentives to boost the structure of recyclers and collection points will increase the economic gain from such activities (Guarnieri et al., 2016). In addition, companies can take advantage of carbon credits by adopting WEEE reverse logistics (Caiado et al., 2017).

The adoption of linear programming by government decision-makers, manufacturers, and recyclers in Macedonia and Greece from 2005 to 2008 assisted in the reduction of transportation costs, container leasing fees, and fossil fuel consumption, resulting in savings of up to 545,000 euros (Achilles et al., 2012). Therefore, the economic advantages are strongly related to the optimal localization of electronic waste recycling plants. Similar simulations have indicated annual costs saving of up to 235 thousand euros in Messologhi and Kavala, Greece (Achilles et al., 2010a). In Turkey, mathematical simulations have been used to identify the best locations for electro-electronic equipment waste recycling plants, such as Ankara, Istanbul, and Izmir (Aras et al., 2015). These settings may have economic advantages related to the distance required in collecting electro-electronic waste, from the disposal point to the recycling plants (Ayvaz et al., 2015). Mathematical modelling simulations using entirely mixed integer linear programming, in which 254 Texan municipalities were listed, yielded 99 possible municipalities suitable for electro-electronic waste recycling and processing plant installations. These installations, when activated, could promote economic advantages, such as waste transportation logistics, disposal, and storage cost reductions (Assavapokee et al., 2012). The fixed costs related to the transportation of WEEE are less when the recyclers have a strategic location (Walther and Spengler, 2005). Moreover, the use of informal recyclers for the collection of WEEE is more profitable for Chinese manufacturers because of the reduction in freight costs (Li and Tee, 2012). However, these studies used mathematical modelling, presenting only estimates of economic gains through percentage data or qualitative data. In addition, they do not propose economic indices for the practical implementation of WEEE reverse logistics for recycling and reuse and to use as performance indicators for the possible economic gains of such implementations.

Dalrymple et al. (2007) and Bouzon et al. (2016) find that the critical aspect is obtaining international technology for the reuse of WEEE, including the processing of PCBs. Goosey and Kellner (2002) and Sohaili et al. (2012) concluded that the primary activities in adopting WEEE reverse logistics are recycling and reuse of PCB because of the opportunity for economic gains with the precious metals extracted from PCB through three different processes. (i) Pyrometallurgy is a traditional technique that uses different processing temperatures to recover non-iron and precious metals from PCB electronic waste (Kamberovic et al., 2009); in addition there is a high consumption of resources to recover precious metals (Devecil et al., 2010); (ii) Hydrometallurgy uses a lixiviation process for dissolution from a mineral, concentrated, or compound by metallurgical elements (Castro and Martins, 2010) that it use much less energy (Chaurasia et al., 2013); (iii) Bio-hydrometallurgy uses microorganisms that extract metals from concentrated minerals (Erüst et al., 2013). Recycling PCB derived from obsolete computers constitutes a relatively new activity in Brazil, and there are possibilities of expansion in this area (Castro and Martins, 2010).

3. Methodology

The present study is classified as empirical in nature, conducted with the purpose of gathering in-depth information in a real-life context, when the limits between phenomena and context are not well defined. The approach is quantitative once the variables are analysed by measurable values. The exploratory research is an initial step when understanding the subject matter does not allow definite conclusions (Yin, 2009).

A conceptual structure was developed using a subset of the bibliographical review, a bibliometric review, which used the following keywords:(1)"reverse logistics"And"e-waste" And "recycling"And"economic";

(2) “reverse logistics” And “e-waste”And “recycling” And “environmental”; (3) “reverse logistics”And“waste electrical and electronic equipment” And“recycling”And“economic”; (4) “reverse logistics”And“waste electrical and electronic equipment”And“recycling”And“environmental”;(5) “reverse logistics”And“waste electrical & electronic equipment”And“recycling” And “economic”; (6) “reverse logistics”And“waste electrical & electronic equipment”And“recycling”And“environmental”; (7) “reverse logistics” And“electronic products”And“recycling”And“economic”; (8) “reverse logistics”And“electronic products”And“recycling”And“environmental”; (9) “reverse logistics”And“electro electronic equipment”And“recycling” And“economic”; (10) “reverse logistics”And“electro electronic equipment” And“recycling”And“environmental”; (11) “reverse logistics”And“weee ”And“recycling” And “economic”; (12) “reverse logistics”And“weee” And“recycling” And “environmental”; (13) “reverse logistics”And“printed circuit board” And“recycling”. Twenty-one scientific publications were found in journals; and in a systematic review; fourteen articles were identified as relevant to the present work.

After the identifying the research gap, three transport managers and three American manufacturers of electro-electronic products located in Sao Paulo, Brazil were interviewed with the aim of mapping the WEEE reverse logistics process for recycling and reuse. Interviews were scheduled over six months and each interview was four hours. This analysis indicated that the manufacturers do not have an internal recycling and reuse process. Only Manufacturer A structured a recycler centre near the plant, Recycler A, who also processes the WEEE from all three manufacturers researched.

Subsequently, interviews and observations with Brazilian Recycler A were scheduled, and they lasted eight hours. The aim was to map a flowchart of WEEE reverse logistics for recycling and reuse, collect financial data, and develop a waste mass balance for analysis. Recycler A performed the recycling of polymers and sales for reuse for Manufacturers A, B and C in a closed cycle. The remaining WEEE are sold to Brazilian Recycler B. Next, interviews and observations were conducted with Brazilian Recycler A, they lasted eight hours and covered the same material as for Recycler B. The Recycler B sells several types of waste to reuse in manufacturing; they perform trituration and classify PCB waste to sell to Recycler C, located in Genebra, Switzerland. Finally, interviews and observations with Swiss Recycler C lasted 2 h. Recycler C extracts precious metals from PCB and transformed them into ingots for sale. This process is an industrial secret. Thus, the operational manager of Recycler C did not provide the financial data and quantity of recovered waste.

Data collection from the three recyclers lasted more than months, analysing the operational process of each recycler; data triangulation was used to quantitatively measure data in the reverse logistics chain, according to Yin (2009) and Miles and Huberman (1994). The method adopted used multiple cases analyses for the six companies. The multiple case method enables a holistic vision of the day-by-day, emphasizing its empirical character in the contemporary phenomena investigation (Yin, 2009).

The pieces of information needed for this research were gathered by interview and observation with the three recyclers (A, B and C); techniques of execution of the processes involving the electronic waste recycling were described.

This data collection technique enables identifying information for higher-order research questions, by directly or indirectly observing the operations, activities or phenomena related to the study of relevant behaviour, which was not purely historical (Yin, 2009). An interview with the in-charge professional was made to make understanding the whole operation easier. Yin (2009), considers an interview one of the most important sources of information to develop multiples cases, in which the prevalence of using such a data collection type is justified by its credibility.

Special attention is given to the estimates of investments made in infrastructure, machinery, labour force and logistics costs, to calculate the eventual advantage economic (EA). Afterward, the percentage rate and return on investment (ROI) period were calculated. ROI analysis is the best way to assess the degree of success of a given enterprise: dividing the obtained profit over a time period, divided by an investment, and calculating the percentage value (Gitman and Zutter, 2010; Oliveira Neto et al., 2016).

In addition, kilograms (mass) of waste processed from obsolete electronic equipment, such as computers, monitors, printers, switches, routers, storages, and servers of any size, was estimated. Therefore, based on Oliveira Neto et al. (2016), the Mass Intensity Factors (MIF) tool was used for an environmental assessment. MIF takes into account mass (M) and the Intensity Factor (IF) as variables, as in Eq. (1):

$$\mathrm{MIF} = (\mathrm{M} \times \mathrm{IF}) \tag{1}$$

MIF makes it possible to measure the environmental impact with regards to abiotic and biotic materials, water, and air consumption, each grouped in compartment form (Ritthoff et al., 2002). The biotic compartment encompasses a set of all living organisms, such as plants and decomposers; the abiotic compartment is a set of non-living ecosystem factors, which acts on the biotic medium, made up of measures such as temperature, pressure, precipitation and geographical relief (Odum et al., 1998). The MIF is simple to apply in industries, which is considered to be an advantage. Other complex methods are not used by industries because of the lack of time afforded by decision-makers.

The environmental impact reduction calculation is obtained by multiplying the factor of each compartment, abiotic (w), biotic (x), water (y), and air (z), by the material’s respective masses. Eq. (2) provides the calculation for each compartment:

$$\mathrm{MIC} = (\mathrm{IF\ Aw} + \mathrm{IF\ Bw} + \mathrm{IF\ Cw} + \ldots + \mathrm{IF\ Nw}) \tag{2}$$

Where:

IF Aw is A waste’s intensity factor in the abiotic compartment (w)
IF Bw is B waste’s intensity factor in the abiotic compartment (w)
IF Cw is C waste’s intensity factor in the abiotic compartment (w)
IF Nw is N waste’s intensity in the abiotic compartment (w)

*MIC example for the abiotic compartment (w), likewise for the others.

The sum of all compartments enables the calculation of the Mass Intensity Total (MIT), as described in Eq. (3):

$$\mathrm{MIT} = (\mathrm{MICW} + \mathrm{MICX} + \mathrm{MICY} + \mathrm{MICZ} + \ldots + \mathrm{MICn}) \tag{3}$$

In order to compare economic advantage (EA) to environmental gain (EG), the economic advantage index (EAI) and environmental gain index (EGI) are used, as described in Eqs. (4) and (5), respectively, where *Total Material Economy (TME) and *Mass Intensity Total (MIT)

$$\mathrm{EAI} = (\mathrm{TME}/\mathrm{EA}) \tag{4}$$

$$\mathrm{EGI} = (\mathrm{MIT}/\mathrm{EA}) \tag{5}$$

After it was developed the sensitivity analysis through of the variation of −30% until 30% to support conclusions of the proposed indexes, according to Syamsuddin (2013) and Sinha et al. (2016).

Electronic products are composed of several components, which, in general, are made of polymers materials, metals, and ceramics. Table 1 shows these materials and their respective MIF factors in each one compartment. All inputs and outputs of the reuse and recycling process were researched, inclusive of electric energy and water consumption.

4. Case study

4.1. Interviews and observations with three American manufacturers of electro-electronic products located in Sao paulo, Brazil

The first study was developed in manufacturing company A, which is responsible for manufacturing and assembling computing electronic device components, printers and servers of small, medium and large

Table 1
Material Intensity Factors used in the study.
Source: Wuppertal Institute, 2015.

Description	Material intensity units [kg/kg]			
	Abiotic	Biotic	Water	Air
ABS Plastic	397		20,689	375
Iron	21,58		50,486	507
Glass	295		1165	074
Copper	34,847		36,716	160
Styrene/butadiene	570		14,600	165
Ferrite (molybdenum)	74,800		128,600	950
Stainless steel	942		7538	065
Low-alloy steel (recycled)	147		5876	052
Silver	7500		0,00	000
Gold	540,000		0,00	000
Palladium	320,301		192,728	1,377,200
Common aluminium	1898		53,921	591
Cast aluminium	811		23,413	293
Forged aluminium	2380		62,700	720
Nickel	14,129		23,334	4083
Lead	1812		135.80	228
Tin	8486		10958,00	14,900
Zinc	2310		000	000
Polypropylenes	209		3580	148
Polystyrenes	251		16,404	280
Polycarbonates	694		21,219	470
PVC	347		30,529	170
Pottery	211		574	005
Cardboard	186	0,75	93,6	033
Fibreglass (resistive)	1084		29,625	201
Water	001		130	000
Diesel oil	136		970	002
	Material intensity units [kg/kWh]			
Electricity	315	004	5764	051

size. In relation to sustainable solutions, it is important to highlight that Manufacturer A designed the first integrated ecosystem of sustainable solutions focused on Brazil's electronic product market using a reuse and recycling centre (Recycler A), where the electronic waste recycling processes are carried out.

The second manufacturing company B designs electronic products, computer software and personal computers. This company, in recent years, has been developing less polluting products and processes with a focus on recycling and reuse of materials at their end-of-life. Further, Manufacturer B sends waste to Recycler A, which specializes in the operation of WEEE reverse logistics for device recycling and reuse.

The third manufacturing company C researches, manufactures and sells hardware and software. Moreover, it offers infrastructure, hosting and consulting services in the field of mainframe computers to nanotechnology. In addition, this company develops environmental friendly products and services through the adoption of WEEE reverse logistic for recycling and reuse. However, this company does not have its own recycling centre, and sends end-of-life products to Recycler A.

In summary, the main manufacturers of electro-electronic products located in Sao Paulo, Brazil do not perform WEEE reverse logistics for recycling and reuse. However, Manufacturer A structured a recycling centre near the factory (Recycler A).

4.2. Interviews and observations with recycler A, located in Sao paulo, Brazil

The electronic waste reuse and recycling centre is built in the same area as Manufacturer A's production plant; it is comprised of an area of 3600 m^2, along with its machinery, safety centre and skilled personnel for receipt, disassembly, and electronic waste treatment processes. The recycling centre is entirely provided with RFID (Radio-Frequency Identification) technology, which is enabled to identify all delivered product characteristics at the dock, as well as develop control reports for its own use at the end of the processes.

At the recycling centre, all processes were observed and notes taken by hand as the enterprise does not allow any kind of recording equipment, such as cellular phones and photographic cameras. The equipment, tools, and devices essential for the recycling processes execution observed include:

a) Polymers shredding equipment: separation belt, feeding belt, grinder, washing machine, decontamination tank, dryer, storing silo, control electric panels.
b) Polymers processing equipment: polymers extruder, cooling basin, granulator and exhausting device for monofilament drying.
c) Additional equipment: Knife sharpener, electric screwdrivers, pliers, bench vise, shelves, conveyor belts, moveable tables for disassembling, big bags of up to 1.5 tons/waste capacity.
d) Transportation equipment: electric and semi-electric forklift trucks.

The recycling centre output capacity is 360 tons of electronic waste per month. Currently, the processed quantity accounts for about 33% of the total capacity, around 120 tons per month. In the agreement made between Manufactures A, B and C and the recycling centre, Manufactures A, B and C are responsible for collecting obsolete products from their suppliers and transporting them to the recycling unit.

The process starts with unloading cargo at the recycling centre reception dock. Next, materials are forwarded to a primary separation and classification process, where paper and cardboard used in packaging are separated. When computers, printers, and other computing equipment are disassembled some components as polymers, printed circuit boards, glasses and metals are removed and separated.

The main recycling activity is polymers waste, where 100% of such material is processed for manufacturing raw polymers material, which will be used in Enterprise A's production line to manufacture new polymers parts for printers, monitor frames, keyboards, and mice.

Polymers go through an accurate visual inspection to ensure that no metal, labels or rubbers remain on the components; if any material remains contaminated they are put aside by colour, mostly white, grey or black. Impure polymers are separated for continued work.

In the following step, the different coloured polymers separately go through a shredding process. Then, the white polymers are subjected to a washing process to eliminate all of the stains and verify adequate purity for raw material generation. Grey and black polymers are washed together. The water used in the washing machine is reused water and treated after each process.

The washed, crunched waste goes through a brief drying process and is sent to the agglutination process for homogenization then forwarded to the extruder. After extrusion, the material is cooled down in reused running water and sent to the granulator. The polymers resin grains produced with the recycled material are used in the manufacturing of new electronic equipment.

Other waste, such as PCB, glass, and metals are sold to Recycler B. However, before shipment, they go through a pressing process to reducing volume; then they are weighed; and, finally, they are ready to be delivered to Recycler B. WEEE Recycler A does not have the machinery and technological knowledge to recycle PCB, glass, and metals. The operational manager of Recycler A mentioned that foreign recyclers consider PCB recycling and reuse an industrial secret, because of the economic gain from selling ingots of precious materials. Foreign recyclers are negotiating sharing this technology with other countries, based on financial gain. Thus, the Brazilian government, through of the Ministry of Technology, is developing meetings with manufacturers of electro-electronic products and recyclers to bring PCB recycling and reuse technology to Brazil. Fig. 1 presents a flowchart from Recycler A. The other processes, such as the treatment of waste derived from PCB will be addressed in further subsections; it is a responsibility assigned to specialized enterprises.

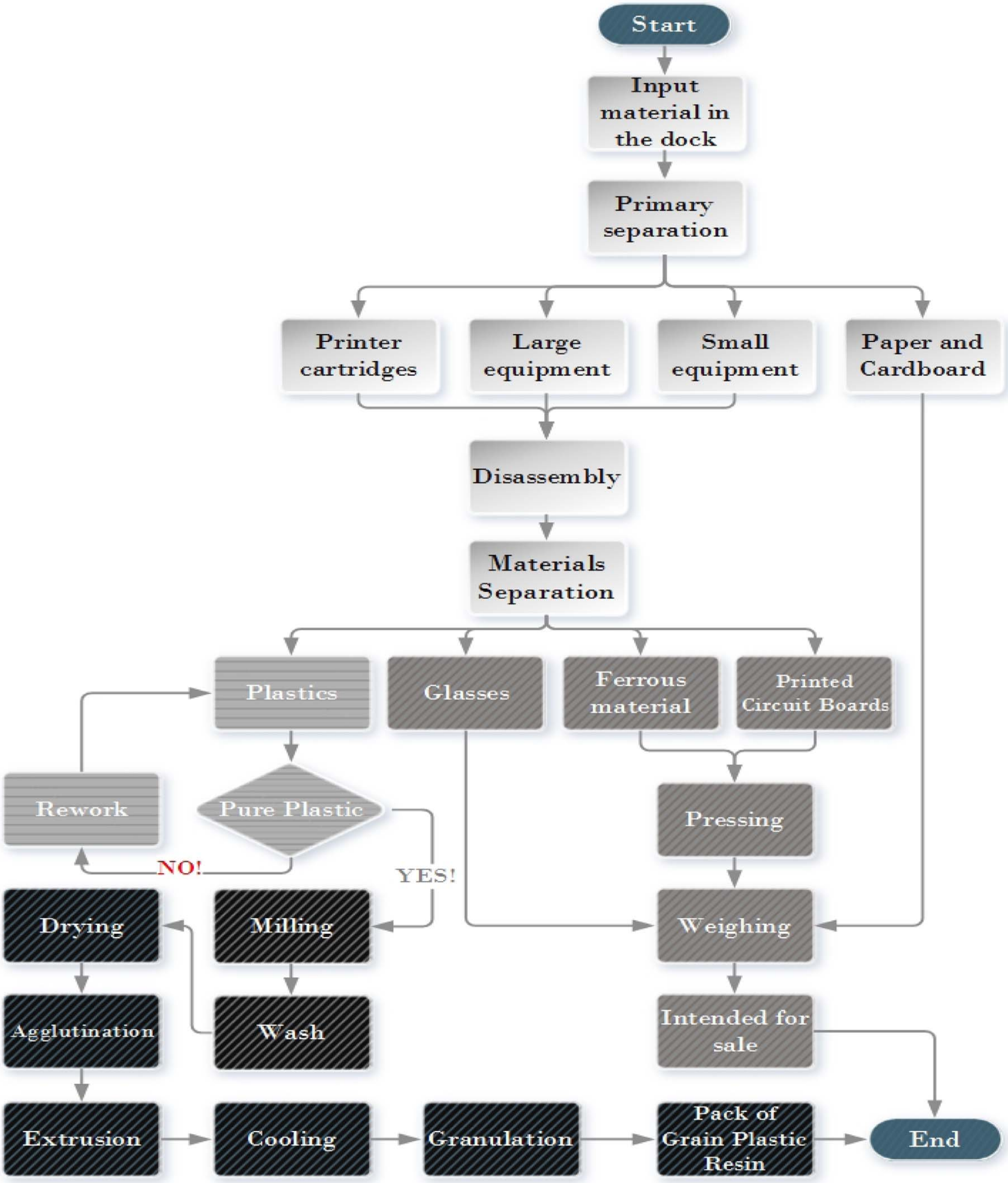

Fig. 1. Recycling Flowchart for Recycler A.
Source: authors.

4.3. *Interviews and observations with recycler B, located in Sao paulo, Brazil*

Recycler B sells paper, cardboard, glass, and iron waste for reuse to manufacturers to produce new products. As reported in Section 4.2, the reuse and recycling centre established by Manufacturer A does not have the machinery or technology required to recycle PCB and metals. Therefore, these waste materials are traded with Recycler B, which holds the technology to process this kind of a waste. PCB electronic waste material is bought by Recycler B, which extracts the materials for the reuse and recycling centre at its own expense. It holds the technology needed to carry out the following steps: weighing, grinding, and classifying waste materials in accordance with each element's characteristics. These materials include magnetic metals, non-magnetic metals, and insulating polymers.

The shredding process reduces the debris size to 1.0–1.5 cm, making the materials easier to separate. Afterwards, these particles are stored in one-ton bags according to waste type. The weighing step is used to record the total waste material exported, in accordance with international regulations stated in the Basel Agreement (2005).

Finally, all electronic waste material is forwarded for final processing to enterprises specializing in the recovery of gold, silver, palladium, copper, lead, tin, and other metals extracted from printed circuit boards. According to surveys, enterprises with the technology to carry out the purification of metals contained in PCBs are located in Europe, Asia, and North America.

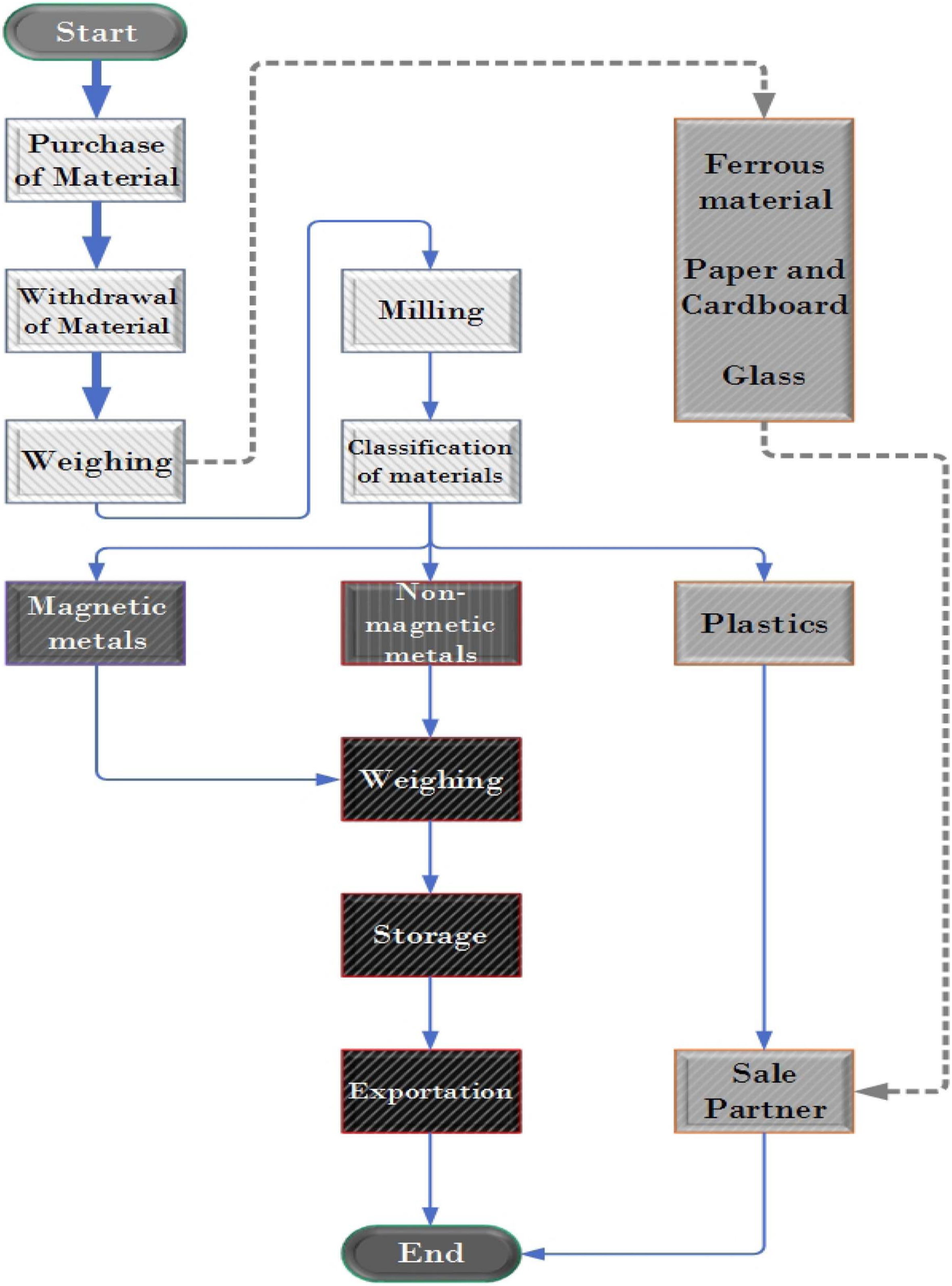

Fig. 2. Recycling Flowchart for Recycler B.
Source: Authors.

Fig. 2 presents a flow chart of Recycler B's processes for electronic waste recycling. Polymer materials account for 23% of the total waste of the PCBs, representing approximately one-quarter of the total waste, according Nnorom and Osibanjo (2008) and Robinson (2009). Owing to their insulating characteristics, they appear in terminal finishing and coatings, as well as in some electronic components. Brazilian Recycler B does not recycle PCBs.

The surveyed parties in Brazil report that the implementing processes related to PCB re expensive, owing the low amount of PCBs for recycling and because raw materials (e.g. acqua regia, which is a mixture of nitric acid and hydrochloric acid) are expensive and strictly controlled by the Brazilian government in terms of importation, especially in large quantities. In addition, in Brazil there are obsolete technologies use for recycling, requiring the importation of machinery and equipment from Europe and the United States, according to the research of Bouzon et al. (2016). This finding is corroborated Canal et al. (2014), indicating that PCB recycling requires a considerable investment by enterprises.

4.4. Interviews and observations with recycler C, located in Genebra, Switzerland

The operational manager of Recycler C only authorized the mapping of the WEEE reverse logistics for recycling and reuse. He did not provide quantitative data in terms of economic gain and mass balance, indicating that was an industrial secret for Recycler C.

At Recycler C, electronic waste materials are eventually subjected to a leaching process to remove the component weldings, and separate the metallic and non-metallic waste materials. This PCB recycling process is called hydrometallurgy (Chaurasia et al., 2013).

At this step, it is possible to extract tin (Sn), lead (Pb), and copper (Cu); the copper fraction is subject to another leaching process to separate other kinds of metals, such as gold (Au), silver (Ag), palladium (Pd), nickel (Ni), Zinc (Zn) and others in smaller fractions. The copper waste goes through a separation process by electrolysis where the particles are agglutinated. Next, chemical solvents used in the process are removed and, eventually, a new electrolysis process agglutinates the extracted copper.

The adoption of electronic waste recycling within a closed cycle results in a minimization of incorrect disposal of harmful waste materials, which can severely affect human health (Kasper et al., 2011).

The recovered material is subjected to a fusion process that produces ingots, or any other shapes, in accordance with the technique used. Overall, the basic flow of PCB recycling processes is described in Fig. 3. There may be variations in the applied techniques based on the quantity of processed waste materials.

4.5. Economic advantages of adopting WEEE reverse logistics for recycling and reuse

The costs of acquiring the raw materials to manufacture polymers parts for new electronic equipment are estimated and compared to the cost of recycled polymers. Recycler A obtained an economic gain of US$ 1,286,080 per year with the sale of recycled polymers and Manufacturers A, B, and C obtained an economic gain of US$ 2,000.000 per year by reusing recycled polymers in their production systems, resulting in an economic advantage of US$ 3,286,080 per year. The economic gains from the sale of PCB wastes from manufacturers to Recycler A were US$ 180,250, from Recycler A to Recycler B were US$ 170,000, and from Recycler B to Recycler C were US$ 600,150, resulting in an economic gain for the chain of US$ 950,400 per year. However, the economic data from Recycler C was not obtained during the interview and observation process. The economic advantage obtained from recycling and producing ingots of precious metals extracted from PCBs are an industrial secret, protected by technological knowledge. Table 2 shows the total economic gain calculated by adopting WEEE reverse logistics for recycling and reuse, amounting to US$ 4,355,814 per year. However, the yearly water consumption cost was US$ 14,400, electricity consumption cost was US$ 620,000, labour costs were US$ 220,000, and logistics costs (freight of the transport) were US$ 334,230.40 per year. The logistics costs were calculated after removing 1800 tons of WEEE from the collection points by manufacturers A, B, and C, with costs of US$ 268,800.00 per year. Then, Recycler A removed 1800 tons of WEEE from the manufacturer, at a cost of US$ 32,239.84. It is important to point out that Recycler A is located in the same plant as Manufacturer A, reducing the logistics cost. In addition, Recycler A sends 1000 tons of polymers per year to manufacturer A to reuse. Then, Recycler B removed 800 tons of WEEE from Recycler A, at a cost of US$ 22,800.96. Of this, 200 tons are PCB, which means 600 tons are steel, iron, glass, cardboard, aluminium, copper, rubber, ferrite, polypropylene, PVC, and pottery. The 200 tons of PCB are sent to Recycler C in Switzerland by means of a free carrier (FCA) because the cost of air freight is the responsibility of Recycler C. Thus, Recycler B pays the transportation to Viracopos airport in Brazil, at a cost of US$ 10,389.60. The total cost of US$ 1,188,630.40 yields a total saving of US$ 3,167,183.61.

The results indicate that the manufacturer obtained a greater economic gain (62%) from selling WEEE and reusing polymers for the production of new products. Thus, the manufacturer utilized the recycled polymers, saving on the purchase of raw polymers (plastic), followed by Recycler A with an average economic gain of 29% through polymer recycling and WEEE sales to Recycler B. Recycler B developed the trituration and classification of PCBs to sell to Recycler C and sold WEEE to the others for remanufacturing, obtaining a lower economic gain (9%). Recycler C extracted the precious metals to produce ingots to sell, but did not realize a financial gain. The results indicate that it is important for Brazilian recyclers to bridge PCB recycling and reuse technology to improve financial profitability.

Thus, Manufacturers A, B, and C focus on their core competence of developing and producing electro-electronic products. Therefore, specialized recyclers to implement WEEE reverse logistics for recycling and reuse offer a business opportunity that would comply with the requirements of the NSWP.

The return on investment was calculated based on the economic gain of the WEEE reverse logistics chain of US$ 3167,4183.61, as shown in Table 2, subtracting the investment of Recyclers A and B in infrastructure (machines and equipment) and warehouse leases, with a value of US$ 4,413,700. Thus, a 10-year machine depreciation was deducted (US$ 441,370), as were tax payments of 30% for income tax, in the amount of US$ 817,744. This resulted in a net economic gain of US$ 1,908,070, with a return on investment of 49.9% per year and a discounted payback of 15% per year over 2.80 years.

4.6. Environmental advantages of reuse and recycling

Environmental analyses were taken into account using all of material present in the electronic waste. The measuring units are kg and kWh. The mass intensity per compartment (MIC) was determined by multiplying the quantity of each material by its respective mass intensity factor (MIC). The mass intensity total (MIT) was determined as the sum of the MIC of the abiotic–biotic–water–air components.

For example, recycling 1.0×10^6 kg per year of ABS polymers reduces the environmental impact by 2.2×10^8 kg. Considering a pollution minimization of 4.0×10^6 kg in the abiotic component, factors that directly affect the life of the ecosystem increase the temperature and atmospheric pressure by 2.1×10^8 kg in water and 3.8×10^6 kg in air.

The electric power (-1.1×10^7 kg/kWh), water consumption (-2.6×10^5 kg), and diesel oil utilized in the transport (-7.6×10^5 kg) are measured as a negative impact; that is, they use natural resources. Electric power and water values are subtracted from the other components, as shown in Table 3. In addition, electricity is consumed during the recycling and reuse operations, resulting in a negative environmental impact of $-\ 2.1 \times 10^3$ kg in the biotic component. However, the results were satisfactory in terms of the reduction in the environmental impact (3.2×10^7 kg) in abiotic component, 3.1×10^8 kg in water, and 4.9×10^6 kg of air, reducing the pollution to the ecosystem by 3.4×10^8 kg.

The high electric power consumption indicated in Table 3, especially in the biotic component, has a total intensity that is negative (-2.1×10^3). This indicates that a reuse and recycling enterprise, despite having an environmental impact reduction equivalent to

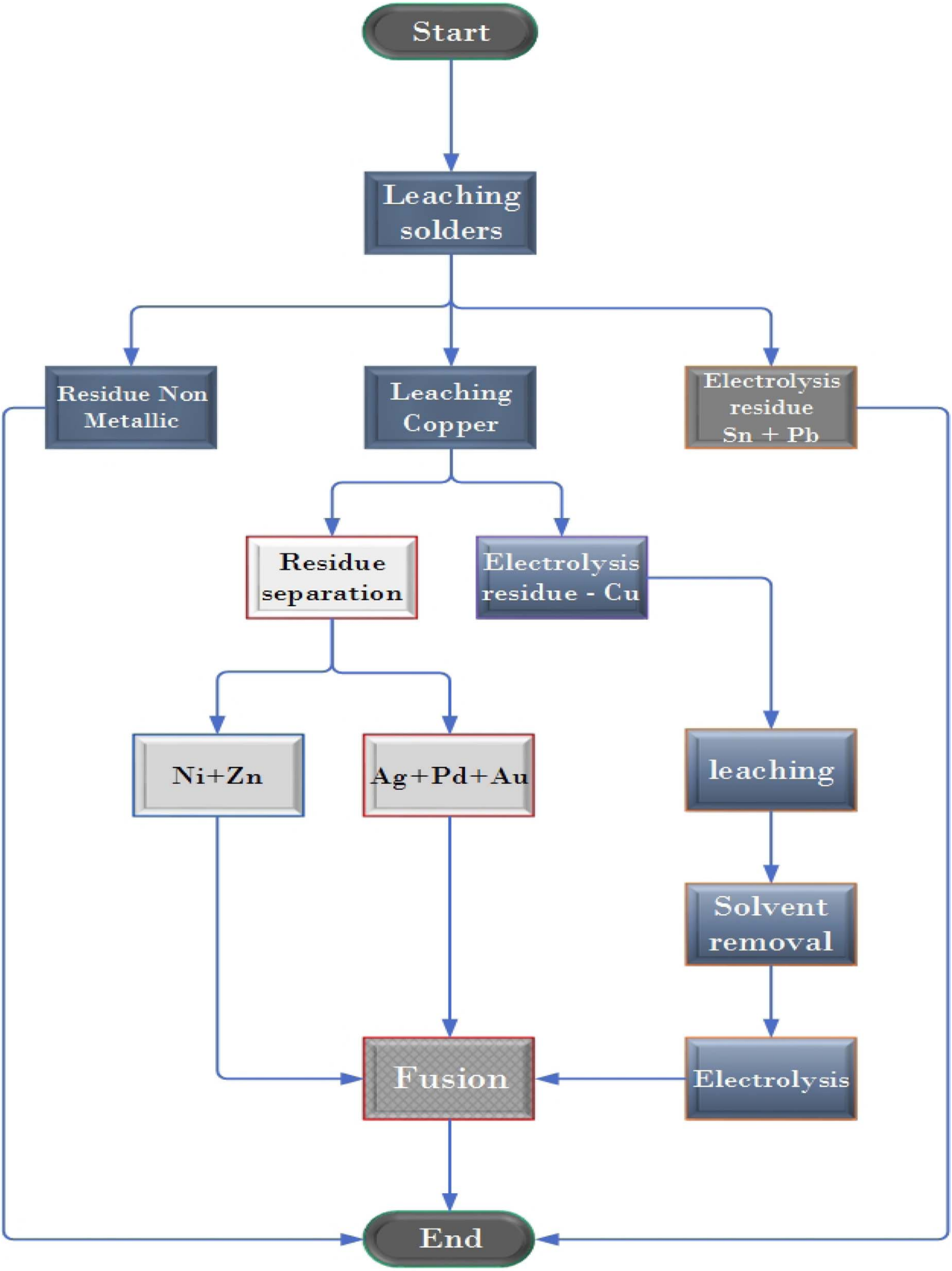

Fig. 3. Recycling Flowchart for Recycler C.
Source: authors.

Table 2
Economic Gain per year of the chain.
Source: Companies data.

Description	Manufactures A, B and C	Brazilian, Sao Paulo Recycler A	Brazilian, Sao Paulo Recycler B	Switzerland, Genebra Recycler C	Economic gain per year of the chain
Polymers (Plastics)	U$2,000.000.00	U$1,286,080.00			U$3,286,080.00
PCB	Sold to Recycler A U$180,250.00	Disassembles, presses and weighs U $350,250.00 -(U$180,250.00) = U $170,000.00	Trituration and classification in magnetic metals, insulations and plastic U$950,400.00 - (U$350,250.00) = $600,150.00	Did not inform	U$950,400.00
Iron	Sold to Recycler A U$6,250.00	Sold to recycler B U$12,500.00 -(U$6,250.00) =U$6,250.00	Sold to remanufacturing and reuse U$28,800.00 - (U$12,500.00) = U$16,300.00	Did not inform	U$28,800.00
Aluminium	Sold to Recycler A U$4,550.00	Sold to recycler B U$9,250.03 - (U$4,550.00) = U$4,700.03	Sold to remanufacturing and reuse U$17,896.03 - (U$9,250.03) = U$8,646.00	Did not inform	U$17,896.03
Copper	Sold to Recycler A U$13,550.00	Sold to recycler B U$27,230.00 -(U $13,550.00) = U$13,680.00	Sold to remanufacturing and reuse U$56,064.73 - (U$27,230.00) = U$28,834.73	Did not inform	U$56,064.73
Stainless steel	Sold to Recycler A U$550.00	Sold to recycler B U$980.80 - (U$550.00) = U $430.80	Sold to remanufacturing and reuse U$2,173.25 − (U$980.80) = U$1,192.45	Did not inform	U$2,173.25
Glass	Sold to Recycler A U$2,280.00	Sold to recycler B U$5,280.60 -(U$2,280.00) = U$3,000.60	Sold to remanufacturing and reuse U$12,240.00 - (U$5,280.60) = U$6,959.40	Did not inform	U$12,240.00
Cardboard	Sold to Recycler A U$480.00	Sold to recycler B U$1,100.00 -(U$480.00) = U$ 620.00	Sold to remanufacturing and reuse U$2,160.00 - (U$1,100.00) U $ 1060,00	Did not inform	U$2,160.00
Economic Gain per year	U$2,207,910.00	U$1,484,761.43	U$663,142.58	Total Economic Gain per year	U$4,355,814.01
Electricity		U$420,000.00	U$200,000.00	Did not inform	U$620,000.00
Manpower		U$100,000.00	U$120,000.00	Did not inform	U$220,000.00
Water		U$10,000.00	U$4,400.00	Did not inform	U$14,400.00
Logistics Costs	Removed of 1800 Tons WEEE of the collecting places U$268,800.00	Removed of 1800 Tons WEEE of the Manufactures U$32,239.84	Removed of 800 Tons WEEE of the Recycler A U$22,800.96 Send of 200 Tons of PCB for the Switzerland by Free Carrier (FCA) named place of delivery U$10,389.60	Did not inform	U$334,230.40
Cost per year	- (U$268,800.00)	- (U$562,239.84)	- (U$357,590.56)	Cost Total per year	- (U$1,188,630.40)
$	U$1,939,110.00	U$922,551.59	U$305,552.02	Economic Gain per year	U$3,167,183.61
%	62%	29%	9%	Did not inform	100%

Table 3
Environmental Advantage Obtained with Reuse and Recycling.
Source: Company data

Components	Annual Mass (Kg/kWh)	Abiotic	Biotic	Water	Air	Annual Reduction (Kg)
ABS Plastics	1,009,740.82	4,008,671.04		208,905.277.42	3.786,528.06	216,700,476.52
Iron	149,882.98	3,234,474.62		75,669,919.26	759,906.69	79,664,300.57
Glass	72,000.00	212,400.00		838,800.00	53,280.00	1,104,480,00
Copper	50,208.09	17,496,013.54		18,434,402.77	80,332.95	36,010,749.25
Rubber	7,200.00	41,040.00		1,051,200.00	11,880.00	1,104,120.00
Ferrite	1,886.54	1,411,134.91		2,426,095.58	17,922.17	3,855,152.66
Stainless steel	1,086.62	10,236.00		81,909.72	706.306	92,852.02
Low alloy steel	100,729.73	148,072.70		5,918,878.82	52,379.46	6,119,330.98
Silver	26.928	201,960.00		0	0	201,960.00
Gold	4.752	2,566,080.00		0	0	2,566,080.00
Palladium	1.584	507,356.78		305,281.15	21,814.85	834,452.78
Common aluminium	2,897.14	54,987.64		1,562,164.70	17,122.07	1,634,274.42
Cast aluminium	4,142.16	33,592.92		969,803.92	12,136.53	1,015,533.37
Forged aluminium	1,908.72	45,427.54		1,196,767.44	13,742.78	1,255,937.76
Nickel	205.92	29,094.44		48,049.37	8,407.71	85,551.52
Lead	107.712	1,951.74		14,627.29	245.583	16,824.61
Tin	318.384	2,701,806.62		3,488,851.87	47,439.22	6,238,097.71
Zinc	421.344	9,733.05		0	0	9,733.05
Polypropylene	14,330.45	29,950.64		513,030.04	21,209.06	564,189.74
Polycarbonate	8,222.54	57,064.46		1,744,741.61	38,645.96	1,840,452.02
PVC	1,412.93	4,902.86		431,352.79	2,401.98	438,657.63
Pottery	460.152	970.921		2,641.27	23.008	3,635.20
Cardboard	7,200.00	13,392.00	5,400.00	673,632.00	2,376.00	694,800.00
Fibreglas (resistive)	807.84	8,756.99		239,322.60	1,623.76	249,703.34
Electricity	187,210.83	−589,714.10	−7,488.43	−10,790,832.01	−96,226.37	−11,484,260.00
Water	200,000.00	−2,000.00		−260,000.00	0	−262,000.00
Diesel oil	324.720	- 441,619.20		−314,978.40	−6,494.40	- 763.092.00
MIC (annual)		32,232,941.11	−2,088.43	313,150,939.00	4,847,403.37	
MIT (annual)						349,791,992.00
TME (annual)						2,147,134.16

3.4×10^8 kg, which is not disposed in nature, is an industry that consumes many natural resources, which are currently scarce in Brazil, especially electric power and water.

4.7. Environmental and economic index

Implementing a reuse and recycling chain yielded a yearly economic advantage (EA) of US$ 3,167,183.61 with the production of polymer raw material used in manufacturing, plus the sales of the remaining waste material to its partners. The environmental advantage obtained by MIT is also evident (3.4×10^8 kg of material), which was neither modified nor extracted from ecosystems. The total material economy (TME) was 2.1×10^6 kg. Thus, the economic advantage index (EAI) = TME/EA = 0.678 kg/US$ and the environmental gain index (EGI) = MIT/EA = 110.44 kg/US$. Fig. 4 shows the sensitivity analysis of the EGI and EAI, ranging from −30% to 30%. Therefore, the indices indicate that the economic gain from adopting WEEE reverse logistics for recycling and reuse is less than the reduction in the environmental impact, because the calculation of the environmental impact considers the sum of the abiotic, biotic, water and air components that represent the global scale of the ecosystem. Thus, the environmental gain is more relevant in terms of the amounts saved in the abiotic, biotic, water, and air components, whereas the economic gain considers only the mass in kg or tons of recycled and reused waste. Therefore, despite the company obtaining an economic gain by adopting WEEE reverse logistics for recycling and reuse, the biggest contribution is in reducing pollution in the environment. Thus, the increase in the quantity (TME) of reused of WEEE in a closed cycle results in an economic gain and a reduction in the environmental impact. However, the reduction in the environmental impact is more relevant, contributing to the NSWP and sustainability.

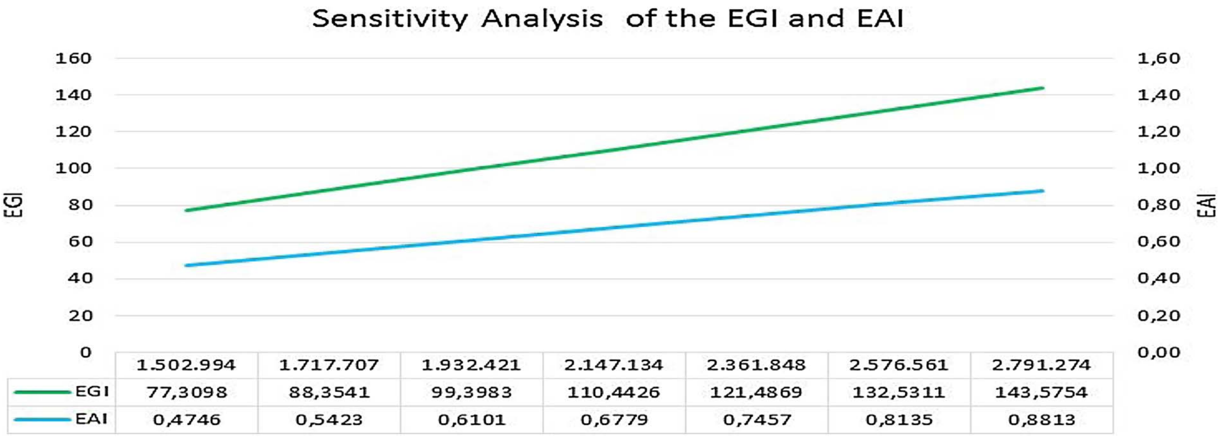

Fig. 4. Sensitivity Analysis of the EGI and EAI.

5. Discussion

The results indicate that the main barrier to adopting WEEE reverse logistics for recycling and reuse by manufacturers and recyclers is the lack of technology for PCB recycling and reuse. The main recycling activity is that of polymers, which requires a simpler technology. After recycling, Manufacturers A, B, and C reuse the recycled polymers. This indicates that manufacturers can develop WEEE reverse logistics for recycling and reuse, contributing to the NSWP (Brasil, 2010). However, it is important that local manufacturers and recyclers, with the support of the government, bring PCB recycling and reuse technology to Brazil. Despite having high added-value, this is paid to the Swiss recycler. Thus, in order to survive in the Brazilian market, recyclers will need this technology to implement WEEE reverse logistics in more companies, contributing to the government's plan and complying with the law.

Other waste, such PCB, glass, and metals, are sold to partner businesses, indicating that the recycling processes are decentralized. Additionally, Recycler A does not hold the technology needed to process the PCB recycling and reuse, which are forwarded to Recycler B. Subsequently, they ship these separated and pressed materials to an international business, Recycler C, because Brazil does not yet have the technological capabilities for final recycling. This finding agrees with that of Castro and Martins (2010), who emphasized that PCB recycling technology in Brazil is still in the study stage, indicating the fragility of solid waste material management. Moreover, Brazilian enterprises handle simpler recycling processes, mainly because PCB recycling requires a high investment by businesses, along with the application of new technologies, according Canal et al. (2014). The final processes of the electronic PCB waste materials consist of the extraction of several metals, and are executed by international Recycler C, located in Geneva, Switzerland. This practical result is in accordance with the experimental research of Castro and Martins (2010).

Furthermore, from the waste materials derived from the PCB, electronics manufacturers need to establish a feasible solid waste material management plan, and there is a need for planning along the whole chain. This signifies an increase in complexity. In this context, the participation of specialized enterprises for processing only some parts of the electronic waste adds new costs to the processes. This result concurs with that of Kasper et al. (2011), who suggest that goals are required to properly invest in recovering precious metals. The inadequate disposal of heavy metals, which negatively impact ecosystems, needs to be reduced.

In addition, adopting WEEE reverses logistics for recycling and reuse by three electro-electronic manufacturers located in Brazil and recyclers resulted in an economic gain for the chain of US$ 3,501,417. The manufacturers of electro-electronic products (A, B, and C), upon using the recycled polymer materials and reducing their purchases of raw materials, saved up to US$ 2,207,910 per year. Recycler A obtained US$ 964,761 of financial gain through polymer recycling and disassembly, pressed weights of PCB, and sales of iron, aluminium, copper, stainless steel, glass, and cardboard to Recycler B. Recycler B obtained US$ 338,742 with the trituration and classification of the PCB wastes to sell to Recycler C in Switzerland, remanufacturing sales, and the reuse of other waste. Recycler C did not provide information on its economic gain from the extraction of precious metals, only indicating that they produce ingots. Another relevant aspect identified is the ROI of the chain. Here, Recyclers A and B obtained 49.9% per year over is 34 months. With regard to economic advantage, scientific articles and virtual simulations using mathematical modelling indicate cost reductions before logistical process optimization and fuels savings (Achilles et al., 2010a,b, 2012; Kilic et al., 2015; Aras et al., 2015; Liu et al., 2016; Assavapokee et al., 2012). This result contributes to the relevant scientific literature, because it presents the economic gain of the chain, considering three manufacturers and three recyclers that adopted WEEE reverse logistics for recycling and reuse. In addition, it contributes to organizational practice, indicating that WEEE recycling and reuse generates a financial profit for the chain. Thus, it can boost the adoption of WEEE reverse logistics for recycling and reuse by manufacturers and recyclers located in Brazil, overcoming the uncertainty in the investment in international technologies for recycling. This result corroborates the research of Bouzon et al. (2016), Souza et al. (2016), and Araujo et al. (2015).

Additionally, the results indicate a significant environmental impact, a 3.5×10^8 kg reduction in abiotic, abiotic, water and air components, with the adoption of WEEE reverse logistics for recycling and reusing by manufacturers and recyclers of electro-electronic products located in Brazil. For the environmental impact, there are qualitative and quantitative approaches and citations. However, it is clear that there are negative consequences derived from fossil fuel pollution and the disposal of electronic waste materials in landfills. WEEE reverse logistics for recycling and reusing reduces CO_2 in virtual simulations and mathematical modelling (Achilles et al., 2010a,b, 2012; Kilic et al., 2015; Aras et al., 2015; Liu et al., 2016; Assavapokee et al., 2012). This research contributes a quantitative measure of the environmental impact of implementing recycling and reuse in the electronics manufacturing industry. In addition, this study presented a simple eco-efficiency toll to apply in practice, which can be used by manufacturing and recycling managers. This finding builds on the findings of Bouzon et al. (2016), Souza et al. (2016), Guarnieri et al. (2016), Ghisolf et al. (2016), Foelster et al. (2016), and Caiado et al. (2017), who generally use mathematical modelling and qualitative data, but do not show practical results.

After calculating the economic gain and the reduction of the environmental impact, an economic advantage index (EAI) was developed, which indicates that each dollar (US$) saved corresponds to 0.678 kg of material. For the environmental gain index (EGI), each dollar (US$) saved provides a benefit of approximately 110 kg of material that is neither processed nor withdrawn from the ecosystems. The adoption of these indices in organizational practice generates continuous improvement in terms of waste management; the greater the recyclability in the closed cycle process, the greater is the index value, leading to a greater reduction in environmental impact. Thus, the manufacturers of electro-electronic products and recyclers can adopt goals for continuous improvement, based on this index. These findings add to the literature because there are no indices to measure the adoption of WEEE reverse logistics, considering the reduction of environmental impact in abiotic, biotic, water, and air compartments and the economic gain. These indices were developed for easy application in organizational practice because the research around the world generally used mathematical modelling tools (Walther and Spengler, 2005; Lau and Wang, 2009; Achillas et al., 2010a,b, 2012; Li and Tee, 2012; Assavapokee et al., 2012; Ayvaz et al., 2015; Liu et al., 2016; Aras et al., 2015; Ghisolf et al., 2016), linear programming (Kilic et al., 2014; Aras et al., 2015), qualitative data (Dalrymple et al., 2007; Wongthasanekorn, 2011; Kochan et al., 2015; Araujo et al., 2015; Guarnieri et al., 2016; Caiado et al., 2017), AHP, Fuzzy, and Delphi (Bouzon et al., 2016; Souza et al., 2016), and life cycle assessments (Foelster et al., 2016).

In summary, these results fill the gap within the literature; the innovations of the present work with regard to environmental and economic issues include applying the mass intensity factor (MIF) to environmental estimates, and providing economic and environmental advantage comparisons using the economic advantage index (EAI), environmental gain index (EGI), and return on investment (ROI).

6. Conclusions

Based on economic and environmental advantages, the results show considerable gains, indicating a promising market niche. The attractive economic advantage and ROI in a relatively short period constitutes an example to be followed by other businesses that are related to the electronic products segment. However, the recyclers may not reuse their polymer waste in the production line because the core competence is recycling. The recyclers sell the recycled polymers to the manufacturer A to produce new products, although Brazilian recyclers may find other advantages. For example, the recyclers have the opportunity of increasing their economic gain by 67% through the growth of the client portfolio in Brazil, because the recycling centre operates at only 33% of its total capability. This will be possible because the NSWP will lead the manufacturers of electro-electronic products to adopt the WEEE reverse logistics for recycling and reuse.

With regard to the environmental advantages, the gain is even higher, because after calculating the EAI and the EGI, it was concluded that the index on reducing the environmental impact in the biotic, abiotic, water, and air compartments (110.44 kg), representing the ecosystem on a global scale, is higher than the economic advantage index (0.678 kg), which considers the mass of recycled and reused waste. Thus, greater recyclability in the closed cycle process means a greater reduction in the environmental impact.

For electronic waste materials, the reverse logistics domain shows that Brazil's businesses have to enhance their electronic waste reuse and recycling processes. These processes are decentralized so that it is difficult to develop a cooperative network. Polymers, cardboard, metals, and PCBs rely on other partner enterprises, which are specialized in each one of these material processing areas.

In addition, the processing for the recovery of the metals contained in the PCBs is carried out by foreign enterprises (Europe, Asia, and North America) exclusively. In addition to the technological barriers, there are environmental rules/laws for overseas transport, stated in ISO14001. Adopting closed-cycle electronic waste recycling minimizes the hazardous disposal of waste, which contributes to sustainable practices. As those interviewed in this study pointed out, there is a need to establish goals for recovering precious metals to minimize inadequate disposal of heavy metals into ecosystems. Within this context, Brazil should invest in PCB recycling technology to increase its economic and environmental advantages in electronic waste materials management.

However, prior studies and surveyed specialists here have indicated that PCB recycling involves a series of processes and techniques for the recovery of precious metals that require the acquisition of specific raw materials not traded in Brazil. This barrier will require a high investment to overcome.

A limitation of this research is that multiples cases studied were conducted with three manufacturers located in Brazil and three recyclers, two located in Brazil and one in Switzerland, with a particular reverse logistics for WEEE. Further research is recommended for other reverse logistics processes in other countries to provide more generalized conclusions in order to reinforce the findings presented here.

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