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RESEARCH ARTICLE

E-waste management and sustainability: a case study in Brazil

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Abstract The advancement of technology and development of new electronic and electrical equipment with a reduced life cycle has increased the need for the disposal of them (called Waste of Electric and Electronic Equipment or simply e-waste) due to defects presented during use, replacement of obsolete equipment, and ease of acquisition of new equipment. There is a lack of consumer awareness regarding the use, handling storage, and disposal of this equipment. In Brazil, the disposal of post-consumer waste is regulated by the National Solid Waste Policy, established by Law No. 12305 and regulated on the 23rd December 2010. Under this legislation, manufacturers and importers are required to perform a project for the Reverse Logistics of e-waste, though its implementation is not well defined. This work focuses on the verification of the sustainability of reverse logistics suggested by the legislation and the mandatory points, evaluating its costs and the possible financial gain with recycling of the waste. The management of reverse logistics and recycling of waste electrical and electronic equipment, or simply recycling of e-waste, as suggested by the government, will be the responsibility of the managing organization to be formed by the manufacturers/importers in Brazil.

Keywords E-waste · Government environmental policies · Sustainability · Recycling · Reverse logistics

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Introduction

One definition that could encompass all of the issues involved is that given by the Step Initiative, which considers that e-waste is a term used to cover almost all types of electric and electronic equipment that has or could enter the waste stream, including televisions, computers, mobile phones, white goods (e.g., fridges, washing machines, dryers, etc.), home entertainment and stereo systems, toys, toasters, kettles, and almost any household or business item with circuitry or electrical components with power or a battery supply. There is a classification used in Brazil (INVENTTA 2014) that is convenient to specify the type of remanufacturing needed for the e-waste:

- Green line: desktops, notebooks, printers, and mobile phones.
- Brown line: televisions, monitors, plasma models, *light emitter diodes* (LED), or *liquid cristal displays* (LCD) types.
- White line: refrigerators, freezers, cookers, and air conditioning equipment.
- Blue line: blenders, electric irons, drilling machines, microwave appliances, and toasters.

This classification does not include batteries, fluorescent lamps, cathode ray tubes, and other hazardous materials, which require specialized treatment. The green line has been emphasized because it is easier to quantify its disposal, unlike washing machines and refrigerators, for example, that go through direct disposal in dumps or landfill and the printed circuit boards are hardly ever extracted.

Global e-waste production was approximately 49 million metric tons in 2012. China and the USA were the ones that brought most electronic equipment on the market with 11.1 and 10 million tons, respectively, and also the ones that generated the most electronic waste, with 7.3 and 9 million tonnes. India and Japan brought 4.3 and 3.3 million tonnes of electronic and electric equipment to the market, respectively, each generating around 2.7 million tonnes of e-waste (USEPA 2014). The sum of the electrical and electronic equipments placed on the market by the Member States of the USA is 12.2 million tonnes, resulting in the generation of approximately 10 million tonnes of e-waste. In this scenario, Brazil produced 2 million tons of these equipments and generated 1.4 million tons of e-waste in the same year (2012). With a growth of 33% in the generation of garbage of this nature in 2015, 65.4 million tons of waste were generated (Araujo et al 2012). The volume of these equipments placed on the market will result in the generation of large volumes of e-waste that can cause problems to the environment and human health risks according *Solving the E-waste Problem* (http://www.step-initiative.org/initiative/what-is-e-waste,php).

Brazil generates the greatest quantity of e-waste among all the emerging countries. In 2015, 65.4 million tons of e-waste were generated (6.5 kg per capita in 2015 and 8 kg per capita in 2017). This may be less than Mexico's 2014 generation rate (8.2 kg per capita), but it is more than the other BRICS (Brazil, Russia, India, China, South Africa) countries, with the exception of Russia (China, 4.4 kg per capita; India, 1.3; South Africa, 6.6; Russia, 8.7).

In order to tackle these issues and to implement adequate e-waste management, the Brazilian Solid Waste National Policy (Ministry of the Environment 2010) enforced the implementation of e-waste reverse logistics under the shared responsibility of electrical and electrical and electronic equipment producers, importers, distributors, and sellers (direct chain), with the broader responsibilities of governments and other actors (Souza et al. 2015). This is a great responsibility because most of the industries are multinational, but each country has specific laws: AOC, Phillips, Samsung, Lenovo, Dell, LG, Motorola, Panasonic, Sony, Semp/Toshiba, and many others that produces washing machines, freezers, cookers, refrigerators, like Consul, Brastemp, Bosch, General Electric, and many others. An association of these importers/manufacturers is difficult, and the Brazilian Association of Electronic and Electric Industries have been assigned this mission.

In this article, we studied the significance of the factors that comprise the environmental sustainability strategies (environmental legislation and green image), the operational features of the closed-loop supply chain, and the economical sustainability of the recycling activities introduced by Georgiadis and Besiou (2008).

Methodology

Assumptions

Recycling of e-waste in developed countries consists of the following major StEPs (Cui and Forssberg 2003; Tsydenova and Bengtsson 2011): (a) disassembly: selective disassembly targeting and singling out hazardous or valuable components for special treatment; (b) upgrading: mechanical processing and/or metallurgical processing to increase the content of desirable materials; and (c) refining: purifying the recovered materials using chemical (metallurgical) processing to make them acceptable for the original use.

In most developing countries, there is a lack of systems covering all steps from disposal until final processing due to limited infrastructure and access to technologies and investment. The principal "Best-of-2-Worlds" philosophy (Bo2W) provides a network and pragmatic solution for e-waste treatment in emerging economies (Nnorom and Osibanjo 2008). It seeks technical and logistic integration of "best" pre-processing in developing countries to manually dismantle e-waste and best end-processing to treat hazardous and complex fractions in international state-of-the-art end-processing facilities (Wang et al. 2012).

Design for environment cleaner production, extended producer responsibility, standards and labeling, product stewardship, recycling, and remanufacturing are some of the practices adopted by various countries around the world to deal with the e-waste stream (Herat 2007) and Almeida et al. (2016). These practices have inspired government regulation, in some aspects. Articles of researchers like Corrêa and Xavier (2013), trace a review of related legislation in Brazil, relevant literature, and a number of Brazilian and international case studies to develop a basic framework to be used in the development and implementation of reverse logistics systems. In this article, the basis for the case study was the government guidelines.

The locally produced e-waste is mostly crushed and exported to countries such as Canada, Belgium, and Singapore (INVENTTA 2014).

According to Schluep et al. (2015), Brazil, Colombia, and Mexico are classified as having the potential to adapt the technologies to their own needs and even complete the full cycle of processing, thus reducing the need to export the waste, following technology and knowledge exchange.

Unfortunately, in Brazil, a large proportion of the waste produced is still mixed with household waste and is destined for landfill sites, or informal "recovery" chains operated by scavengers, cooperatives, and scrap dealers. The estimated collection rate for the country is 2%. At present, Brazil does not recycle, only collects, separates, and exports e-waste (de Oliveira et al. 2016).

Some importers and manufacters use product delivery channels at resellers to collect the redundant material for disposal. Importers/manufacturers such as Apple, Motorola, and Sony have chosen to collect their products, which hampers the development of an integrated action through an importer/manufacturer association.

In addition, for the common consumer, awareness campaigns are needed. These should include dissemination in the media, and efforts by the producer/manufacturer to make the consumer of a cell phone, for example, when buying a new cell phone, to be aware of the need to return the old one to the supplier.

Initially, the Ministry of Environment of Brazil, through its Notice no. 1/2013, published the Call to Sector Agreement on Developing the Logistics System for the Reverse Deployment of Electronic Products and components (Ministry of the Environment 2013). The main aspects of this document, which proposes that the manufacturers and/or importers of electrical and electronic equipment establish a reverse logistics system for their products, are:

- The operation of collection centers in cities with fewer than 25,000 inhabitants;
- The operation of screening centers in cities of over 25,000 inhabitants;
- Encouraging the operation of waste of electrical and electronic equipment recycling industries;
- The establishment of organizations for logistics management of the products, with social inclusion and training; and
- The possibility of compensation for the products obtained for all stakeholders in the process.

Companies would have 5 years to implement the new system, in fact a reverse logistics system, having to set up points for garbage collection and to decide who is responsible for collections.

Obviously, the number of collection centers and screening system was super-dimensioned, due to the e-waste production of Brazil. This article proposes estimates of the costs for the reverse logistics, within a closed chain, to verify the sustainability of all stages of the process.

The case of Minas Gerais

Minas Gerais was one of the first Brazilian states to deal with e-waste. The state developed a project in partnership with the Swiss State Secretariat for Economic Affairs (SECO) in order to map the situation of e-waste in the state and suggest management systems (The World Bank 2012).

The model proposed by the Brazilian government for reverse logistics of e-waste divides responsibilities between consumers (primary logistics), merchants (receiving points and primary freight), and the manufacturer/importer (primary freight, packaging, secondary freight, packaging, and transport to processing end). This takes into account the full service of shared responsibility guidelines placed by the laws and the feasibility of implementation across the deadlines for the system beginning to operate (Ministry of the Environment 2013). Brazil is a country with 8,500,000 km^2 of surface and presents great difficulties in transporting products in the green regions due to the tropical rain forest. The most developed region is the Southeast, with the states of São Paulo, Rio de Janeiro, and Minas Gerais (Brazilian Institute of Geography and Statistics (IBGE) 2011). Figure 1 shows the political division of Brazil:

For the accomplishment of the research, the state of Minas Gerais, in the Southeast of Brazil, was chosen, due to the following factors:

- Minas Gerais has the third largest GDP of Brazil at US$389.00 per capita (Brazilian Institute of Geography and Statistics (IBGE) 2016);
- The state has the largest road network in the country;
- The state has the largest number of municipalities in the country (853) and economic differences between regions;
- The state has geographical dimensions almost equal to France—586,519,727 km^2;
- The population of the state is nearly 20 million inhabitants, and therefore has a low geographical density as in Fig. 2:

The State Environmental Foundation of Minas Gerais (State Foundation of the Environment (FEAM) 2009), based on the potential e-waste entering the market (projection) for the year of 2016, estimates about 892,000.00 tons of generated e-waste in Brazil, 22.3% of the total generated in the metropolitan region of Belo Horizonte (capital of the state of Minas Gerais), with 5873,841 inhabitants (Brazilian Institute of Geography and Statistics (IBGE) 2016). These data are estimated due to the fact that the last census in Brazil took place in 2010. The total estimated generation (great and small e-waste) for Brazil is 1,376,000.13 tons/year (Brazilian Institute of Geography and Statistics (IBGE) 2016). In the state of Minas Gerais, the estimates are about 302,720.02 tons of generated e-waste from all types, with 29% of the total generated in the metropolitan region of Belo Horizonte. If considering only cellphones and telephones, televisions, and computers, then the estimated generation in Brazil is approximately 41,000 tons/year, from a population of

Fig. 1 Regions of Brazil. Source: Brazilian Institute of Geography and Statistics (IBGE) 2011

205,544,410 inhabitants (Brazilian Institute of Geography and Statistics (IBGE) 2016). The projected values from 2001 to 2030, with only cellphones (mixed with telephones), television, and computers, are, respectively, 1.0 kg/inhabitant, 1.0 kg/inhabitant, and 1.1 kg/inhabitant (Almeida et al 2016). This study considers 1 kg/inhabitant for each year, which is an adequate number for the current situation.

Calculations

According experiences with mass spectrometry analysis of materials randomly collected at recycling industries and processed in the Federal University of Outro Preto (UFOP) laboratories, the average composition of elements in electronic devices and market prices are shown in Table 1.

Fig. 2 Main cities at the state of Minas Gerais. Source: Brazilian Institute of Geography and Statistics (IBGE) 2011

Table 1 Medium values of 1 ton existing materials in e-waste (green line—small: laptops, desktops, cell phones, DVD (*digital video displays*) players)

Composition of tertiary recycling electronics per ton material (desktops, laptops, cell phones)			
		US$/kg	Total (US$)
1.16 kg	Ag	480	556.80
113.3 g	Au	28.360	3213.18
46.6 g	Pd	86.820	4045.81
43 kg	Cu	8.80	378.40
126 kg	Steel	0.06058	7.63
24.10 kg	Al	0.6038	14.55
1.5 kg	Ni	0.5321	6.79
460 kg	Plastics (PET, PE, PP)	0.51468	23.67
			8246.73

The recovered materials evaluation occurs in function of related market prices, which are characterized by a high volatility (Cucchiella et al. 2015).

This study does not take into account batteries, whose recycling is more complex, and are costly items to the process (Espinosa and Tenório 2006). Battery recycling processes can follow three distinct lines: based on ore processing operations, hydrometallurgical, and pyrometallurgical. Sometimes, although these processes are specific for recycling batteries, the batteries are also sometimes recycled along with other types of materials (Espinosa and Tenório 2006).

This paper calculates the logistic costs involved in the modeling shown in Fig. 3, proposed by the government (Ministry of the Environment 2013). The focus of existing reverse logistics research has been on the economic and environmental aspects of sustainability—social sustainability has yet to be comprehensively examined. There is a gap in the literature of reverse logistics practices to verify the social impact of this reverse logistics (Sarkis et al. 2010). Each city with fewer than 25,000 inhabitants must have a collection center, which, when it reaches its storage limit, sends the material without any physicochemical transformation to industry in the capital of the state of Minas Gerais, Belo Horizonte. Cities with over 25,000 inhabitants will have screening centers, which may separate plastic, metal, and printed circuit boards, where they would also obtain materials such as polymers and metal plates, received from waste pickers, companies and waste traders, polymers, steel and metals for the manufacturing of steel, or aluminum products. The printed circuit boards would be directed to a specialist industry in Belo Horizonte. Metals such as Au, Pt, Ag, Ni, and others would be extracted there. These metals and other materials obtained may return to the regional centers for use by industries and for manufacturers/importers themselves, as the raw material is recycled to make new products. It is shown in Fig. 3.

At Minas Gerais, the Gross Domestic Product per capita is average for Brazil, allowing us to make a projection of reasonable generation of e-waste depending on the income of individuals (Brazilian Institute of Geography and Statistics (IBGE) 2011).

The infrastructure, services, and recycling collection systems provided have been evaluated by a number of researchers in different countries; their research provides detailed information about certain interventions and possible improvements for high performance and maximum public participation. However, there has been no significant experience of public participation in designing a recycling scheme, according Keramitsoglou and Tsagarakis (2013). Then, the studied model is a production of the Federal Government, with a call to the corporations for efforts in organizing the structure for the reverse logistics system to be developed in Brazil. The costs of receiving centers to be created are shown in Table 2. There will be collection centers, with the aim of gathering primary storage material, which may come from boxes in supermarkets, shopping malls, or sent from the consumer

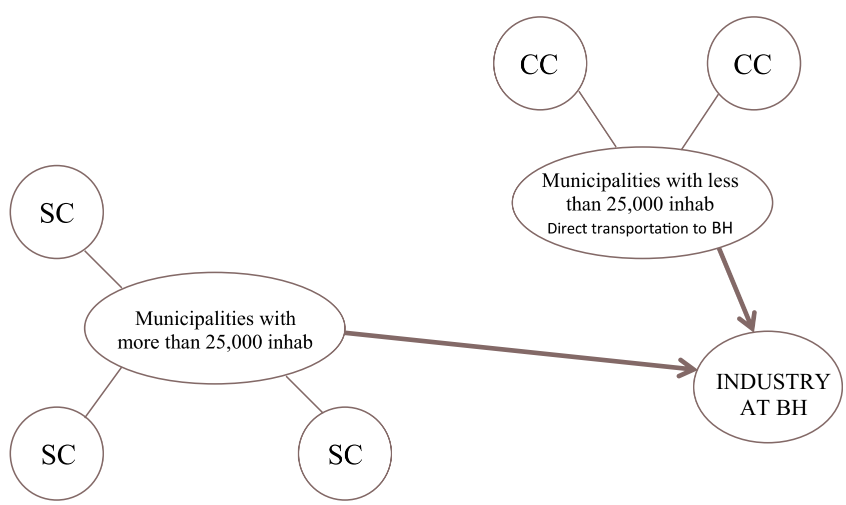


Fig. 3 Basic modeling proposal from the government guidelines. *CC* collection center, *SC* screaning center

Table 2 Investment expenditures and operational expenditures at the collection center

Equipment	Quantity	Value/unit (US$)	Total annual value (US$)
Workers	1	877.19	10,526.31
Space (m^2)	16	146.19	1754.38
Office material	1	14.61	175.43
Security (m^2)	16	4.38	842.19
Total value			13,298.31

him/herself. This material would be cataloged and can be tracked. There are implementation costs that must be properly calculated. In the feasibility analysis, it is possible to determine the level of charge and the costs for CC; the most viable has a capacity of 5 tons. These costs were researched for the Brazilian market and are shown in Table 2.

The screening centers will have other costs, harvested at local market, according to the need for separation and storage; the capacity was chosen at 12,000 tons considering investment and operating according to Tables 3 and 4:

The determination of collection center numbers and screening centers were calculated (mandatory by the Call Notice no. 1/2013) with the criteria: cities with more than 25,000 inhabitants will have a number of sorting centers, dependent on the population (The maximum is 2.5 million inhabitants at Belo Horizonte). There are 148 municipalities with 25,000 or more inhabitants in Minas Gerais (Brazilian Institute of Geography and Statistics (IBGE) 2010), and in the larger cities, there will be sorting centers, which will operate the sorting, tracking, and separating parts of e-waste that do not involve disassembly or transformation. When exhausted in its capacity, the material will be sent to the recycling plant in Belo Horizonte or to its metropolitan area. The smallest municipalities, with fewer than 25,000 inhabits, will have only collection centers and will transport the material directly to Belo Horizonte, when their capacity is reached (Ministry of the Environment 2013). There are 705 municipalities with fewer than 25,000 inhabits (Brazilian Institute of Geography and Statistics (IBGE) 2011). In a simulation made to viabilize the reverse logistics were used instead for all cities with over 25,000 inhabitants, only the 18 regional poles of the state of Minas Gerais (a classification based on the regions of influence of cities (Brazilian Institute of Geography and Statistics (IBGE) 2011)), shown on Table 5. The criterion was the existence of infrastructure at the city to receive e-waste from other smaller cities in its surroundings. The number of screening centers were chosen, with their smaller capacity, for standardization of the centers. As for the vehicle capacity for road freight, models were estimated of 5 tons capacity, an average value, and able to travel with a small amount of removed material from collection center to take them to the nearest regional screening center. Once there, the material will be screened

Table 3 Investment expenditures of screening centers

Equipment	Anual capacity (ton; 12,000)			
	Quantity	Unit value (US$)	Total value (US$)	Percent
Forklift	2	11,695.90	23,391.80	44
Mat	2	5847,95	11,695.90	22
Palletiser	2	4385,96	8771.92	16
Human-powered cars	10	350.87	3508.70	7
Scales	2	1315.78	2631.56	5
Shipping containers	20	87.71	1754.20	3
Office material	1	1461.98	1461.98	3
Total value			53,216.06	

Table 4 Operational costs for screaning center

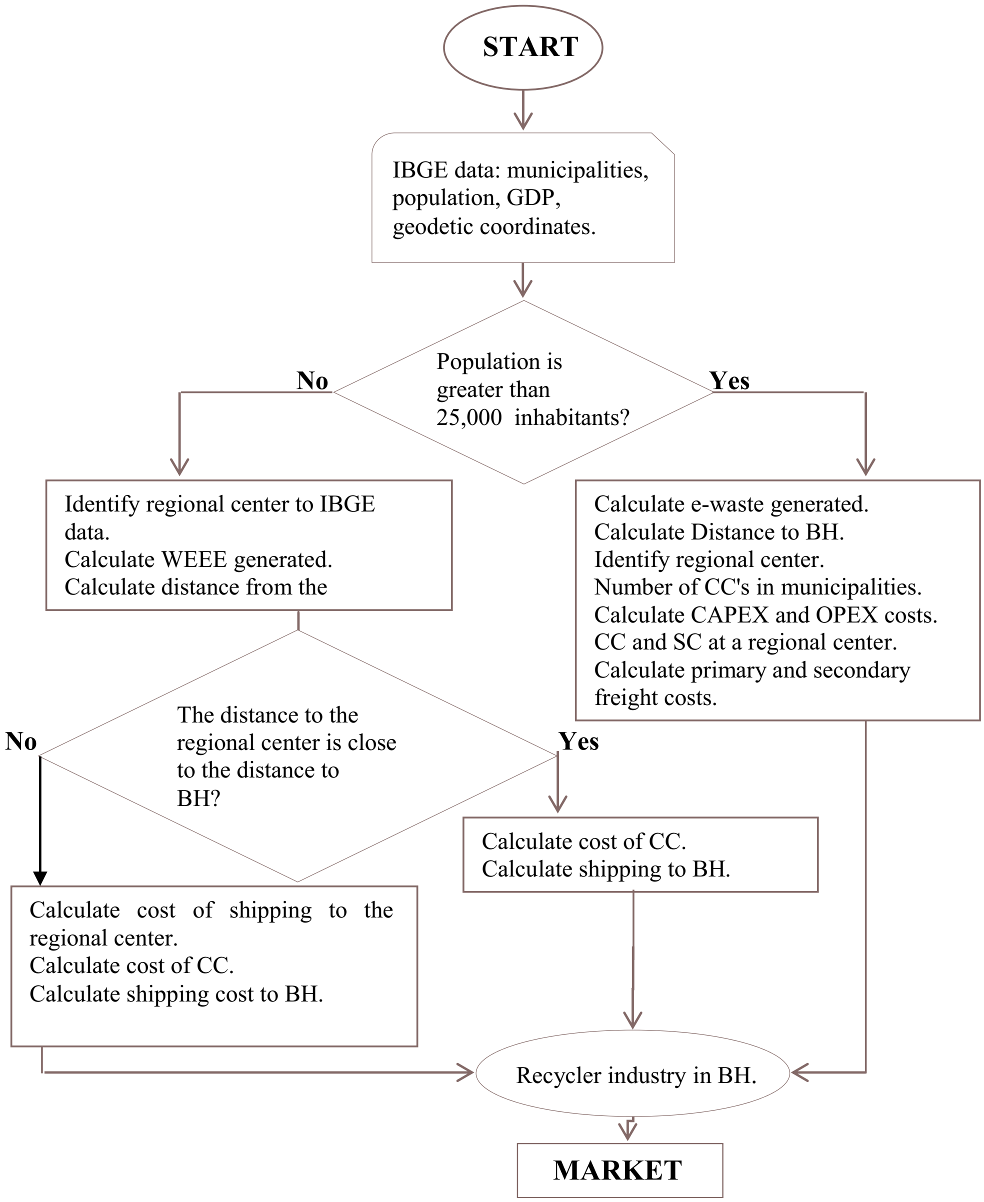
	Anual capacity (ton; 12,000)			
	Quantity	Unit value (US$)	Total value (US$)	Percent (%)
Officials +	18	402.66	4831.92	20
taxes shed	18%	13.86	967.20	20
	400 m^2	7.53	3013.33	9
Other costs	20.00%	591.40	7096.80	17
Total value			162,506.93	

Source: INVENTTA (2014)

Table 5 Regional poles at Minas Gerais, with e-waste amount

	Population (inhabitants)	E-waste at 2015 (kg)
Belo Horizonte	2,375,151	226,351,599
Conselheiro Lafaiete	116,512	14,699,091
Diamantina	45,880	4,927,461
Divinópolis	8974	621,500
Governador Valadares	263,689	41,539,784
Ipatinga	239,468	78,402,302
Juiz de Fora	516,247	110,862,433
Manhuaçu	79,574	15,996,816
Montes Claros	361,915	58,685,506
Muriaé	100,765	14,022,734
Paracatu	84,718	25,120,370
Passos	106,290	18,989,377
Poços de Caldas	152,435	51,275,785
Pouso Alegre	130,615	41,791,145
Teófilo Otoni	134,745	16,281,804
Uberaba	295,988	103,052,576
Uberlândia	604,013	235,627,018
Varginha	123,081	44,077,979
	5,740,060	875,973,681

Fig. 4 Algorithm for the proposed model



and the parts that cause soil contamination separated or those parts that affect SC transport to recycling plants in the metropolitan area of Belo Horizonte (BH). Calculations of the primary (from collection centers to screening centers) and secondary freight (from screening centers to industry) costs due to the generation of e-waste use the current average per capita generation of 1.0 kg/inhabitant for a total of 853 municipalities in Minas Gerais. The distances for freight were calculated using its geodesic coordinates or with data from Minas Gerais Department of Highways, and the freight costs from Central of Costs and Prices of Truck Drivers (CCPC 2015). Road transportation was chosen in medium-size trucks with 5-ton loads. The costs of facillities and handwork were surveyed in the local market.

In Table 5, an estimate of the total e-waste was made, according to the estimated population in 2015, and its generation of e-waste (Brazilian Institute of Geography and Statistics (IBGE) 2016):

Municipalities shown on the left are regional poles with more than 25,000 inhabitants, and on the right, the distribution of e-waste according to population and their waste generation capacity. Figure 4 shows an algoritm for the proposed model.

The calculations were made according to Tables 6 and 7, showing examples of the calculation sheets used.

Table 8 shows the results of primary and secondary freight and facility costs for the two city sizes cited in the Call Notice no. 1/2013 of the Federal Government.

The assumptions used were that in 2017, 100% of e-waste collected would be treated (not performed) with a 50% membership fee, and 70% recycling rate for small e-waste as government analysis (INVENTTA 2014).

Table 6 Calculation of costs in reverse logistics for cities with less than 25,000 inhabitants (an example of sheet)

Municipality	Distance to the capital of the state	Population 2010	GDP at current values	Generation of REE/year (kg)	Number of CC	Anual cost of CC	Voyages to the capital/year	Anual cost of freight	Emission of CO_2 (kg)
Abadia dos Dourados	547.00	6704	94,668	6704.00	1	68,674.80	1.00	1218.52	1471.43
Abaeté	213.00	22,690	270,868	22,69000	1	68,674.80	2.00	1308.58	572.97
Abre Campo	216.00	13,311	136,540	13,311.00	1	68,674.80	2.00	1308.58	581.04
Acaiaca	158.00	3920	26,045	3920.00	1	68,674.80	1.00	466.21	425.02
Açucena	280.00	10,276	61,775	10,276.00	1	68,674.80	1.00	654.29	753.20
Água Boa	379.00	15,195	103,708	15,195.00	1	68,674.80	2.00	1684.74	1019.51
Água Comprida	513.00	2025	154,986	2025.00	1	68,674.80	1.00	1218.52	1379.97
Aguanil	239.00	4054	45,189	4054.00	1	68,674.80	1.00	654.29	642.91
Águas Formosas	610.00	18,479	122,321	18,479.00	1	68,674.80	2.00	2813.2	1640.90
Águas Vermelhas	756.00	12,722	95,462	12,72200	1	68,674.80	2.00	3189.36	2033.64
Aimorés	489.00	24,959	304,207	24,959.00	1	68,674.80	2.00	2060.90	1315.41
Aiuruoca	370.00	6162	57,765	6162.00	1	68,674.80	1.00	842.37	995.30

The market for the products

In Brazil, there is already a market for e-waste, represented by companies that play a part in recycling. These companies are buyers for the e-waste in the market, from large companies that dispose off obsolete material, governmental or private, as well as small companies that collect and sell them. Before this recycling process was established, the materials of great added value and importance to the companies were exported due to the lack of an infrastructure in Brazil that could return them to the productive chain. In fact, the electronics are generally manufactured outside Brazil and assembled here. The activity of these e-waste purchasing companies are shown in Table 9.

An industry at Sorocaba, state of São Paulo, is doing the final recycling and paying for the e-waste. SINCTRONICS Ltd (2015) is expanding its business in the country, and the main operation is in Cingapura. Besides the factory in Sorocaba/SP, there are two others in Rezende/RJ and Manaus/AM.

Another company active in Brazil is UMICORE Co., with its center of operation in Belgium, which collects and pays for printed circuit boards and now has offices in São Paulo and Belo Horizonte.

Results

For all cities of the state of Minas Gerais, the results of the primary and secondary freight costs, maintenance, and operation of collection and screening centers are shown in Table 10. Also, the possible value that can be extracted from e-waste is calculated in Fig. 1 and is at the first line on the left.

Initially, the model proposed by the Federal Government is economically and financially viable and have gain possibility, as shown above, recalling that the costs are all the responsibility of the producer/importer, with no government investments. There are many potential sources of errors in this model, such as an exaggerated number of collection centers and e-waste disposal at the cities, but this first study proves the economic and environmental sustainability of the first and primary government propposal. To establish a recycling process, regardless of the model adopted, it is necessary to organize efficient collection management. The main difficulty associated with the implementation of e-waste recycling processes in Brazil is the collection system, as its efficiency depends not only on the education and cooperation of the people but also on cooperation among industrial waste generators, distributors, and the government. Over half a million waste pickers have been reported in Brazil, and they are responsible for the success of metal scrap collection in the country. The country also has close to 2400 companies and cooperatives involved in the initial recycling and scrap trading. On the other hand, the collection and recycling of e-waste is still incipient in Brazil because e-wastes are not yet seen as a valuable resource in the informal sector (de Oliveira et al. 2012).

The setting used can be considered simple but was suggested in the Notice. Studies by consultants such as INVENTTA (2014), and commissioned by the Brazilian Industrial Development Agency in 2014, worked with estimates of changes in membership and percentage of recycling along the years. These proposals were intended to subsidize sector companies to develop a sectoral agreement for model management.

Table 7 Calculation of costs in reverse logistics for cities with more than 25,000 inhabitants (an example of sheet)

Municipality	Population	Regional pole	Distance to SC	Trips to SC	Number of CC	Costs for CC (5 ton) R$	Costs for primary freight/year (R$)	Distance to the capital	E-waste generatio/ year (kg)	Generation of ewaste/year/ pole (kg)	CAPEX costs of SC (R$)	CT OPEX anual costs (R$)	Trips number to capital/ year	anual costs for secondary freights (R$)
						19,440.00								
Barão de Cocais	28,442	Barão de Cocais	0	3	1	19,440.00	–	98.7	13.936,58					
Santa Bárbara	27,876	Barão de Cocais	11.6	3	1	19.440,00	9135.70	98.7	13.659,24	108,997.56	182,000.00	846,720.00	2	52,640.66
Cidades menos de 25000hab	166.126	Barão de Cocais			23	1,046,040.00	4333.24		81,401.74					
Betim	378,089	Belo Horizonte	31.5	37	2	38,880.00	305,967.06	0	185,263.61					
Cambuí	26,488	Belo Horizonte	431	3	1	–	598,258.17	0	12,979.12					
Campos Gerais	27,600	Belo Horizonte	308	3	1	–	427,525.56	0	13,524.00					
Contagem	603,442	Belo Horizonte	19.2	59	3	–	297,382.66	0	295,686.58					
Coração de Jesus	26,033	Belo Horizonte	424	3	1	–	588,541.68	0	12,756.17					
Esmeraldas	60,271	Belo Horizonte	57.9	6	2	–	91,199.45	0	29,532.79					
Ibirité	158,954	Belo Horizonte	20.1	16	3	–	84,426.43	0	77,887.46					
Igarapé	34,851	Belo Horizonte	46.9	3	1	–	36,936.56	0	17,076.99					
Itajubá	90,658	Belo Horizonte	445	9	1	–	1,853,073.45	0	44,422.42					
Itaúna	85,463	Belo Horizonte	78.5	8	1	–	164,862.56	0	41,876.87					
Lagoa Santa	52,520	Belo Horizonte	39.6	5	1	–	51,978.96	0	25,734.80					
Matozinhos	33,955	Belo Horizonte	47.7	3	1	–	37,566.61	0	16,637.95					
Nova Lima	80,998	Belo Horizonte	26.2	8	1	–	55,024.19	0	39,689.02					
Passos	106,290	Belo Horizonte	348	10	2	–	1,610,161.20	0	52,082.10					
Pitangui	25,311	Belo Horizonte	124	2	1	–	114,747.12	0	12,402.39					
Poços de Caldas	152,435	Belo Horizonte	461	15	2	–	3,199,501.35	0	74,693.15					
Prata	25,802	Belo Horizonte	622	3	1	–	863,379.54	0	12,642.98					
Sabará	126,269	Belo Horizonte	22.6	12	1	–	71,195.42	0	61,871.81					
Santa Luzia	202,942	Belo Horizonte	29.8	20	1	–	156,461.92	0	99,441.58					
Santana do Paraíso	27,265	Belo Horizonte	235	3	1	–	326,196.45	0	13,359.85					
São Francisco	53,828	Belo Horizonte	590	5	1	–	1,364,935.50	0	26,375.72					
São Joaquim de Bicas	25,537	Belo Horizonte	41.3	3	1	–	32,526.23	0	12,513.13					
Sarzedo	25,814	Belo Horizonte	37.9	3	1	–	29,848.52	0	12,648.86	1,191,098.65	182,000.00	846,720.00	0	–
Brumadinho	33,973	Belo Horizonte	0	3	3	–	14,568.75	55.5	16,646.77	16,646.77	182,000.00	846,720.00	2	29,600.37
Cidades menos de 25000hab	319.824	Belo Horizonte			39	1,773,720.00	15,168.23		156,713.76					

Table 8 Total costs for the two sizes of municipalities in Minas Gerais

	Tons	US$	Tons
Municipalities with fewer than 25,000 inhabitants			
Generation of e-waste/year	6057.7		
Annual costs for CR		12,523,051.1	
Annual costs for primary freight		191,287.6	
Emissions on CO_2 (year)			711,628.7
Municipalities with more than 25,000 inhabitants (regional poles)			
Generation of e-waste/year	10,878.6		
Annual operational expenditures and capital expenditures for CT		7,187,276.4	
Annual costs for secondary freight		1,497,477.2	
Total		1,399,092.5	716,844.6

In 2017, however, the assumptions had not reached the predictions of the Federal Government.

In the study commissioned by the Brazilian Industrial Development Agency on page 106, we have:

> "The total operating cost, considering the detailed evolution of assumptions in the study, will evolve to a level of about 65 million dolars to approximately 160 million dolars (at national level) when the system in system, that is, when the whole territory Brazil is covered by the system. These values represent on average 0.5% of the turnover of electronic consumption, used as the basis for this study." (INVENTTA 2014).

The values are consistent with the results in Table 10 in the row total costs: US$92,564,268.30, for the Southeast region (Minas Gerais) and R$500 million that represent around US$150,000,000 level (Brazil), validating the results achieved in our study.

This simulation reported the value of material to be obtained in the final recycling, which is not seen in other studies. The cost of reverse logistics is high but is only a small percentage (0.5%) of revenues with electronics, as pointed out by the study. The study also highlights that the cost of final processing to refine and to obtain metals was not considered by the difficulty of obtaining e-waste export data.

Table 9 Companies that buy e-waste after disassembling made by pickers or small recyclers

Company	The recycling process	Recycling products of greater value aggregate and of greater importance to the company	Destination of recycled products
TCG Recycling	The material is separated and the hazardous waste is sent to industries outside Brazil. There are only 4 large companies in the world.	Precious metals from internal circuit boards.	Umicore, Belgium (www.umicore.com) and Noranda, Canada (www.norandarecycling.com).
Suzaquim	Servers, microcomputers, notebooks, monitors, printers, and other equipment undergo revision, revitalization, and technological updating processes and a warranty of at least 1 year has been placed on the market. Separation of materials is done. For example, plastics go to recyclers, monitors tubes are cut in a wet way and generate metal oxides, the plates pass through grinding and internal separation to mechanically remove the metals that are aggregated in the raw material. From there, the whole process is chemical. After the reprocessing of the technological residues, salts and metal oxides are obtained that will be used in the color, ceramic, refractory, and chemical industries.	Metal is the product that has the highest added value. The company does not work with the commercialization of fine chemicals but incorporates this material to the chemical process for the generation of the final product, the metal oxides.	It exports only end product which are metal oxides to countries like Japan, Denmark, and England.
Cimélia Reciclagem	Separation of electronic scrap by class, milling, and export to the plant (in Singapore), where detoxification takes place (process of raising temperature in a sealed chamber at 1200 °C and cooling in 4 s to 700 °C, dioxin filtration, liquidification, separation by density, separation by electrolysis, decanting, refining, and solidification in bars.	All metals are important with specific use; however, the metals of greater commercial value are palladium and platinum in their various forms (powder, bar, liquid).	Plant in Singapore and later to the Asian and European Market.

Table 10 Total costs of the logistical model/year in Minas Gerais

	Processed tons (16,936.44)	US$139,670,248.00
Annual costs for CR		US$26,240,447.80
Annual costs for freight		US$60,273,549.40
Annual costs for CT		US$6050,271.10
Total costs		US$92,564,268.30
Average costs for reverse logistics/ton		US$5465.39
Gain possibilities/ton		US$2781.33

However, a recycling company in Belo Horizonte, E-MILE, exports 10 tonnes of circuit boards without preprocessing, filling a 40-tonne container, due to the volume occupied (cubing). After delivery to a company outside of Brazil, a mass balance calculation is made, and depending on the composition of the boards, certified by laboratory analysis, a value of around US$6185.04 is returned, which corresponds to a 70% recycling rate for the material sent.

Applying reverse logistics costs of US$5256.88/ton according to Table 8, this mode of operation is clearly profitable, a fact confirmed by the representative of UMICORE Co. at Brazil (UMICORE 2015).

The installation of industries for the processing of printed circuit boards in Brazil will increase earnings as legal export costs, environmental taxes, and charges will be replaced by environmental taxes and charges in Brazil and maritime freight costs are eliminated.

Conclusions

The proposed modeling followed the initial premises of the Brazilian environmental agency and invited companies from the electronics industry to join, in order to develop the management of electronic waste across the country. Although there is no signed agreement yet that covers most of these wastes, many other models target their economic and financial viability in the implementation of reverse logistics. Some large productive electronics companies such as Phillips, Toshiba, Samsung, and Apple are working independently and doing the reverse logistics process for their products. It should, however, be more widely deployed in large industries for the final recycling of metals, closing the circle for the recovery and re-use of e-waste.

The limitations of this study are the lack of coordination between the producing/importing companies in order to propose a more efficient reverse logistics system than the one proposed by the government and the tendency for them to work alone in this area, due to their desire to preserve industrial secrets. Also, there are a lack of studies on the life cycle in the design of the apparatus and other commercial difficulties. The e-waste generated by companies not installed in Brazil, or by deactiveted companies, will require investments of all companies and concerns about environmental protection. In a country with continental dimensions, Minas Gerais—a state in the most developed region of Brazil, the Southeast—was chosen for the study. The reverse logistics approach to other regions of the country with greater distances, less waste, fewer people, and poor roads should be carefully evaluated in other studies.

Another limitation in the study is that Brazil is an assembler of imported material that uses several of the metals likely to be obtained from recycling. Ideally, the country would produce integrated circuits or components that would use those reclaimed metals, which would avoid the transit of materials between continents, already in a state where they would be strong polluters of the environment in the case of transport accidents.

The jobs generation

This study proposes that, having proved that it is economically viable to recycle e-waste, more companies should resolve to invest in new factories for the final recycling of the material. It is estimated that 15,000 direct formal jobs and 45,000 indirect (INVENTTA 2014) would be created by the development of the closed recycling process in Brazil. Using the constitution of collector cooperatives, as was done for aluminum cans, it is possible to encourage the social inclusion of thousands of people.

Future studies

The proposed model must be critically tested and modified as required for it to be optimized in practical terms. It can serve as a stimulus to logistics and market studies, which implement an efficient collection and recycling system in Brazil and generate more effective income. In the future, industries that are currently operating in Brazil using material from abroad could lower their costs by using recycled materials obtained from the fine chemical industries installed here.

There are no studies, so far, which effectively point out financial figures for the process of collecting and recycling waste electronic materials. This study makes considerable advances in this direction in relation to the existing literature.

Final metal recycling processes must, however, be improved and researched. Industrial units must be optimized for improved efficiency and lower production costs.

References

Almeida CMVB et al (2016) Cleaner production towards a sustainable transition. J Clean Prod 112:1

Araújo MG, Magrini A, Mahler CF, Bilitewski B (2012) A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. Waste Manag 32:335–342

Brazilian Institute of Geography and Statistics (IBGE) (2010) Population count 2010. Avaiable at: <http://www.ibge.gov.br/home/estatistica/populacao/contagem2007/contagemfinal/tabela1119.pdf>. Accessed 11 May 2016 (in Portuguese)

Brazilian Institute of Geography and Statistics (IBGE) (2011) Indicators of sustainable development Brazil. Avaiable at: <http://www.ibge.gov.br/home/geociencias/Recursosnaturais/ids/default_2010.shtm>. Accessed 03 June 2015 (in Portuguese)

Brazilian Institute of Geography and Statistics (IBGE) (2016) Geosciences: projection of the population 2016. Avaiable at: <http://www.ibge.gov.br/home/estatistica/populacao>. Accessed 7 July 2017 (in Portuguese)

Central of Costs and Prices of Truck Drivers (CCPC) (2015) Available at: <http://www.guiadotrc.com.br/>. Accessed Feb 2016 (in Portuguese)

Corrêa HL, Xavier LH (2013) Concepts, design and implementation of Reverse Logistics Systems for sustainable supply chains in Brazil. JOSCM: J Oper Supply Chain Manag 6(1):1

Cucchiella F et al (2015) Recycling of WEEEs: An economic assessment of present and future e-waste streams. Renew Sust Energ Rev 51: 263–272

Cui J, Forssberg E (2003) Mechanical recycling of waste electric and electronic equipment: a review. J Hazard Mater 99(3):243–263

de Oliveira CR, Bernardes AM, Gerbase AE (2012) Collection and recycling of electronic scrap: a worldwide overview and comparison with the Brazilian situation. Waste Manag 32(8):1592–1610

de Oliveira CR, Bernardes AM, de Souza RG et al (2016) Sustainability assessment and prioritisation of e-waste management options in Brazil. Waste Manag. https://doi.org/10.1016/j.wasman.2016.01.034

Espinosa DCR, Tenório JAS (2006) Recycling of nickel–cadmium batteries using coal as reducing agent. J Power Sources 157(1):600–604

Georgiadis P, Besiou M (2008) Sustainability in electrical and electronic equipment closed-loop supply chains: A System Dynamics approach. J Clean Prod 16(15):1665–1678

Herat S (2007) Sustainable management of electronic waste (e-waste). Clean Soil Air Water 35:305–310. https://doi.org/10.1002/clen.200700022

INVENTTA (2014) Reverse logistics of electrical and electronic equipment, technical and economic feasibility analysis, Brazil (in Portuguese). Available at http://www.mdic.gov.br/arquivos/dwnl_1416934886.pdf. Accessed 21 Aug 2017

Keramitsoglou KM, Tsagarakis KP (2013) Public participation in designing a recycling scheme towards maximum public acceptance. Resour Conserv Recycl 70:55–67

Ministry of the Environment (2010) Law 12,305. Establishes the national solid waste policy (in Portuguese). Ministry of Environment, Brazil

Ministry of the Environment (2013) Call for the elaboration of a sectoral agreement for the implementation of a reverse logistics system for electrical and electronic products and their components—notice 01/2013 (in Portuguese). Ministry of the Environment, Brazil

Nnorom IC, Osibanjo O (2008) Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour Conserv Recycl 52(6):843–858

Sarkis J, Helms MM, Hervani AA (2010) Reverse logistics and social sustainability. Corp Soc Responsib Environ Manag 17(6):337–354

Schluep M, Hagelueken C, Kuehr R, Magalini F, Maurer C, Meskers C, Mueller E, Wang F (2015) Sustainable innovation and technology transfer industrial sector studies. Recycling from e-waste to resources. United Nations Environment Programme and United Nations University, p. 120

SINCTRONICS Ltd (2015) Available at http://www.sinctronics.com.br. Accessed 17 Mar 2015 (in Portuguese)

Souza RG, Rosenhead J, Salhofer SP, Valle RAB, Lins MPE (2015) Definition of sustainability impact categories based on stakeholder perspectives. J Clean Prod 105:41–51. https://doi.org/10.1016/j.jclepro.2014.09.051

State Foundation of the Environment (FEAM) (2009) Diagnosis of the generation of electrical and electronic waste in Minas Gerais, Brazil (in Portuguese). Available at: <http://www.mma.gov.br/port/conama/processos/.../DiagGer_REE_MG_FEAM_EMPA.pdf>. Accessed 12 Apr 2015

The World Bank (2012) Wasting no opportunity: the case for managing Brazil's electronic waste. Washington, DC, USA

Tsydenova O, Bengtsson M (2011) Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag 31:45–58

UMICORE (2015) Welcome to UMICORE Basil. Presentation available at: http://www.umicore.com.br. Accessed 4 Apr 2015 (in Portuguese)

US Environmental Protection Agency (USEPA) (2014) Wastes—resource conservation—common wastes & materials—eCycling. Available at: <http:///waste/conserve/materials/ecycling/index.htm>. Accessed 4 Apr 2015

Wang F et al (2012) The Best-of-2-Worlds philosophy: developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. Waste Manag 32(11): 2134–2146