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Reverse remanufacturing of electrical and electronic equipment and the circular economy

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Abstract

Purpose – The purpose of the article is to analyze the chain of electrical and electronic equipment (EEE) and its waste (WEEE), within the product chain of Recicladora Urbana (Reurbi), and its interaction with the circular economy.

Design/methodology/approach – Exploratory research with a qualitative approach, based on the study case method, was conducted. The following stages were carried out: definition of the study object; bibliographic survey; documentary survey; technical visit to Reurbi; contacts with experts; creation of research instruments and research execution.

Findings – The main recipients of remanufactured EEE are third sector organizations that run social programs and schools with few financial resources. Recycling firms receive parts and components from the WEEE handled by Reurbi.

Research limitations/implications – The authors only addressed the WEEE reverse remanufacturing chain of Reurbi; therefore, the authors cannot extend the results to an industrial sector.

Practical implications – One practical contribution is disclosing the remanufacturing processes of EEE and the recycling processes of its waste, fostered by the National Solid Waste Policy (PNRS), under a circular economy policy.

Social implications – There is a large market potential for reverse logistics of WEEE and end-of-life EEE as a source of raw material, which is yet to be explored in Brazil, for creating new jobs and revenue.

Originality/value – The publication of articles with the main reflections from the results can provide new discussions and provide opportunities for new studies regarding the Brazilian Solid Waste Policy.

Keywords Circular economy, Electrical and electronic equipment, Waste management, Reverse logistics, Raw material, National policy for solid waste, Reuse, Recycling, Remanufacturing, Solid waste, Sustainability

Paper type Research paper

1. Introduction

Issues like recycling and sustainable development are growing in importance. They are more prominent in developing countries, where there are many informal recycling activities and few environmental laws to regulate waste management (Guarnieri, Silva, Xavier & Chaves, 2020).

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The continuous increase in the generation of solid waste in a society with high consumption affects the population's quality of life negatively, besides causing considerable damage to the environment (Campos, 2014a).

The trend towards depletion of raw materials and inefficient waste management practices are some of the factors that are forcing companies to face these challenges and rethink their business models, leaving the traditional linear process and adopting the principles of a circular economy (Rosa, Sassanelli & Terzi, 2019). According to the Ellen MacArthur Foundation (EMF, 2013), in the last 150 years of industrial evolution, this linear model of production and consumption prevailed, where goods are manufactured from raw materials, sold, used and then discarded as waste.

Among the goods that people generally discard after use are electrical and electronic equipment (EEE) and its waste (WEEE) (Islam & Huda, 2018). The recovery of waste from these products has aroused the interest of society (Atlason, Giacalone & Parajuly, 2017; Mathieux, Recchioni & Ardente, 2014), since they contain both toxic and valuable materials (Islam & Huda, 2018, 2019; Zhang, Geng, Zhong, Dong & Liu, 2019). There are metals, such as copper, gold and silver, as well as critical materials, such as tungsten, niobium and cobalt. Hence, in the last two decades, many countries have established ways to recover these strategic and critical materials from electronic waste (Guarnieri, Silva, Xavier & Chaves, 2020).

Reverse logistics is one of the recovery processes that enable the reverse flow of WEEE and EEE, at the end of its useful life, which have the possibility of postremanufacturing reuse along the supply chain, or by end consumers (Ilgin & Gupta, 2013).

This study analyzed the reverse remanufacturing chain of this equipment and its waste, within the product chain of Recicladora Urbana [Reurbi], located in the city of Jacareí, State of São Paulo, Brazil, and its interaction with the circular economy. It is a relevant study, since the objective of waste management has changed, in recent years, from safe disposal to more attractive options and from an environmental and economic standpoint in order to recover energy and materials (Engeland, Belien, Boeck & Jaeger, 2020). This goal fits the concept of circular economy, where the value of products, materials and resources is kept in the economy, as long as possible.

EEE, whose WEEE we assessed here, are classified into four goods, as defined by the Brazilian Agency for Industrial Development (ABDI, 2013), as shown in Table 1.

We divided the article as follows: after this introduction, Section 2 presents the theoretical background; Section 3 addresses the methodological procedures; section four presents the results and discussion and section five discusses the final remarks.

2. Theoretical framework

2.1 Waste generation and the national policy for solid waste

The term "sustainability" relates to the continuity of an organization in different sectors (private, public or third sector); it is the result of the balance between the three classic

Goods	White	Brown	Blue	Green
Equipment	Refrigerators and freezers, stoves, washing machines and dishwashers, tumble driers, air conditioners	Tube, plasma, LCD and LED monitors and televisions; DVD and VHS equipment; audio equipment; video cameras	Mixers, blenders, electric irons, drills, hair dryers, fruit juicers, vacuum cleaners, coffee makers	Computers, desktop and laptops, computer accessories, tablets and cell phones

Source(s): ABDI (2013)

Table 1. Electrical and electronic goods

dimensions of sustainability – environmental, economic and social – known as the triple bottom line (Elkington, 1998).

Sustainability is related to sustainable development, which regards the rational use (extraction and use) of nonrenewable natural resources, in order to meet the needs of human beings, without squandering, and create wealth for future generations (Florissi, 2009).

In Brazil, urbanization was not followed by public policies to regulate cities' growth, thus leading to an urban territorial expansion towards the periphery, creating large metropolitan regions (Santos, 2020). This phenomenon was due to factors such as the migration of populations from rural areas into urban areas and the growth of industrialization in large cities in the last century. As a result, cities gained importance, as they became an area for wealth and job creation. However, over the years, they began to face a series of challenges because of the large number of inhabitants, which gave rise to several negative aspects such as environmental degradation, social exclusion, insecurity, traffic jam and increased generation of solid waste, such as WEEE (Abiko & Moraes, 2009).

The Brazilian Association of Technical Standards (ABNT) defines solid waste in NBR 10004: Solid Waste - Classification as the waste resulting from industrial, domestic, hospital, commercial, agricultural, service and sweeping activities (ABNT, 2004).

The Ministry of the Environment (MMA, 2016) observes that the correct disposal of solid waste is a primary condition for a sustainable city, as the search for environmentally, socially and financially appropriate solutions in this area reflects society's demand, which requires changes fostered by high socioeconomic and environmental costs. If handled properly, solid waste acquires commercial value and become new raw materials or new inputs, when returning to the production chain.

In Brazil, the National Solid Waste Policy (PNRS) guides solid waste management. As established by Law nº. 12,305/2010, the PNRS defined a set of principles, objectives, instruments, goals and actions that should be adopted for an environmentally sound management of solid waste. It establishes shared responsibility for products' life cycle and charges local governments – Federal District and cities – for the integrated management of solid waste generated in their territories.

One of the relevant concepts for solid waste management is reverse logistics. PNRS requires manufacturers, importers, distributors and traders to structure and implement reverse logistics systems by returning the products after consumers' use, thus ensuring the reuse or environmentally correct waste disposal.

Rogers and Tibben Lembke (1998) mention one of the classical definitions of reverse logistics, by *The Council of Logistics Management*. It is the process of planning, implementing, and controlling the efficient and economic flow of raw materials, inventory of materials in process, of finished products and information related to this flow, from the place of the product's final consumption back to the origin of production, with the goal of recovering values or encouraging the appropriate product discard. Reverse logistics offers great potential for cutting costs, increasing revenues and creating additional profitability for companies and their supply chains (Srivastava, 2013).

Engeland, Belien, Boeck, and Jaeger (2020) created an expanded concept of reverse supply chain (RSC) of waste, as a network composed of all entities involved in the stream of discarded products that leave the point of consumption. It includes collection, transportation, recovery and disposal of waste, and its goal is to recover or create value and encourage a proper final disposal. Reverse logistics is one of the elements of an RSC (Ilgin & Gupta, 2013).

The potential recovery of valuable material resources and sustainable business practices over the past 20 years revealed that the concept of reverse logistics has been accepted and practiced in manufacturing industries (Islam & Huda, 2018). It is recognized as an important part of the circular economy, by providing the reevaluation of WEEE and inserting it in a new production process (Guarnieri, Silva, Xavier & Chaves, 2020). Therefore, it is crucial to improve the collection, treatment and recycling of products at the end of their useful life (Qiang & Zhou, 2016).

WEEE generation can be increased, mainly of those from information and communication technology (ICT) equipment, due to the planned obsolescence of EEE (Zuidwijk & Krikke, 2008). Planned obsolescence is the production of goods with an economically short useful life, which forces consumers to repeat purchases several times (Bulow, 1986), since a new generation makes an older one economically obsolete, although it is not physically obsolete yet (Lee & Lee, 1998).

Among the elements that affect the process of reusing WEEE negatively is the fact that companies with an environmental license for processing and treating it do not process circuit boards, motherboards and computer video cards. These components have 17 metals in their composition and are sent to countries, like Germany, Belgium, China and Japan, to remove these and other components with high market value. In Brazil, collectors gather the material to pass it on to scrap dealers and to companies that disassemble it for recycling; this market is another element that hinders reverse logistics and does not stimulate EEE control for returning it to the manufacturer (Xavier, Carbajosa, Guarnieri & Duarte, 2013).

In addition to reverse logistics, the PNRS also introduced shared responsibility during the product life cycle, establishing obligations to the various actors:

> [. . .] a set of individual and linked attributions of manufacturers, importers, distributors and traders, of consumers, and of those in charge of public services of urban cleaning and solid waste management, for minimizing the volume of solid waste and reducing the impacts to human health and environmental quality that result from products' life cycle, under the terms of this Law [. . .].

Therefore, shared responsibility involves all actors in the various solid waste chains, seeking to optimize the use of recyclables, minimize the volumes of waste and guide an environmentally appropriate disposal of unsuitable waste.

Another item of PNRS is the sectorial agreement. Its purpose is to implement a nationwide reverse logistics system for EEE and to regulate this process through a sectorial agreement, term of commitment or regulation.

2.2 EEE reverse remanufacturing and WEEE collection

The recovery of products and components seeks to add environmental and economic values to the product's disposal phase, and end-of-life strategies are alternatives that support it. The literature discusses different end-of-life strategies, as well as their main characteristics. Reuse, repair, reform/refurbishment, recycling and remanufacturing are among the most used (Saavedra, Barquet, Rozenfeld, Forcellini & Ometto, 2013) and can create profitable business opportunities (Srivastava, 2013). For remanufacturing or recycling companies, the RSC is the most important, as it recovers parts or materials from end-of-life products from the chain. In RSCs, environmental laws and guidelines are as important as minimizing costs and maximizing profits (Ilgin & Gupta, 2013).

The perspective of remanufacturing is to restore products to become new, providing consumers with the same quality and guarantee offered by the manufacturer of the original equipment (Ilgin & Gupta, 2013; Saavedra, Barquet, Rozenfeld, Forcellini & Ometto, 2013). It is a relevant strategy for saving resources and improving the performance of a product's life cycle (Ardente, Peiró, Mathieux & Polverini, 2018).

EEE reverse remanufacturing regards the recovery of products and components of this equipment. The remanufacturing process starts with the collection of the housing or core (used product). The following steps are the complete disassembly of the product, cleaning of parts, inspection and storage of parts, reconditioning and change of parts, and product reassembly. In addition, tests are carried out throughout the process to ensure product quality (Saavedra, Barquet, Rozenfeld, Forcellini & Ometto, 2013). For Zhang, Geng, Zhong, Dong, and Liu (2019), if this waste is not properly treated, the valuable materials within it will be lost, implying that more raw materials will have to be extracted and processed for making new products.

The main actors involved in EEE reverse remanufacturing are as follows: (1) the Brazilian Electrical and Electronic Industry Association (ABINEE, 2017) and Green Eletron, which represent manufacturers and importers; (2) collectors' cooperatives and independent or informal collectors, acknowledged as relevant actors for implementing PNRS; (3) disassembly companies, which sort, decharacterize and sell parts of EEE and WEEE and (4) actual recyclers of metals, plastics and components.

As for the collection of WEEE, Demajorovic, Augusto and Ventre (2016) consider that cooperatives can help overcoming some challenges that are present in the reverse flow of post-consumption materials in Brazil. This view assumes that cooperatives can take over the activities of collection, separation and marketing of these materials, when companies that generated it have no interest in carrying out these processes. For these authors, this relationship may contribute to support cooperatives' operations, which is one of the main problems of nearly all of them; however, sectorial agreements, foreseen in PNRS, may affect the results of collectors' cooperatives negatively.

According to their research, legislation, despite being critical, still does not encourage companies to seek reverse logistics solutions effectively. In addition, distributors, wholesalers, retailers and commerce that make up the reverse chain are still far from the debate. Their participation would be essential to expand waste delivery to cooperatives. Collectors' cooperatives are important for managing solid waste; hence, a partnership between these organizations, manufacturers and importers of electrical electronic products can contribute to making reverse logistics feasible, minimizing environmental impacts and providing better working conditions for the collectors who work there. Cooperatives that are already structured and equipped with appropriate equipment and infrastructure can carry out the activity efficiently and safely, bringing benefits to partners and society.

Although the current management of recovery processes of end-of-life products depends mainly on conventional techniques for waste collection and processing, the growing discussion on circular economy provides options such as reuse, reform and remanufacturing, which are increasingly relevant for electronic products (Atlason, Giacalone & Parajuly, 2017).

2.3 Circular economy and WEEE reuse

The traditional economy, known as linear, describes systems that generate products and waste, which ultimately result in disposal and pollution, being harmful to both human health and the environment (Sikdar, 2019). The production system associated with the traditional economy is running out of resources, causing price volatility, uncertainty and economic crises (Fischer & Pascucci, 2017).

Pearce and Turner (1990, as cited in Su, Heshmati, Geng & Yu, 2013) showed the need to create a closed economic system, where the economy and the environment were not related by linear interconnections, but by a circular relationship. They proposed a closed circuit of material flows in the economy, which they called "circular economy."

The circular economy aims to increase the efficiency of resource use, focusing mainly on urban and industrial waste, to achieve a better balance and harmony between the economy, the environment and society (Ghisellini, Cialani & Ulgiati, 2016). It is an approach that fosters the responsible and cyclical use of resources (Moraga, Huysveld, Mathieux, Blengini, Alaerts, Van Acker, Meester & Dewulf, 2019) and is a concept driven by the European Union and by other governments, such as China, Japan, the United Kingdom, France, Canada, Netherlands, Sweden and Finland, as well as by several companies (Korhonen, Honkasalo & Seppälä, 2018).

It consists of a continuous cycle of positive development that preserves and values natural capital, improves resource creation and reduces systemic risks by managing finite stocks and renewable flows, working effectively at any scale. This economic model seeks to untie global economic development from the consumption of finite resources (EMF, 2015).

One expectation about the circular economy is that it promotes economic growth by creating new businesses and job opportunities, decreases the cost of materials, reduces price volatility, improves security of supply and, at the same time, reduces pressures and environmental impacts (Kalmykova, Sadagopan & Rosado, 2018). It is an evolving theme, which enables reconciling environmental preservation and economic growth (Silva, Shibao, Kruglianskas, Barbieri & Sinisgalli, 2019).

The literature on circular economy does not show a consensus about one single definition. Kirchherr, Reike and Hekkert (2017) gathered 114 definitions in their study. They proposed to define it as an economic system that replaces the concept of end-of-life products through reduction, alternative reuse, recycling and recovery of materials in the production, distribution and consumption processes. It operates at three levels: micro (products, companies and consumers); meso (eco-industrial parks) and macro (city, region, country and beyond). The goal is to achieve sustainable development, by creating environmental quality, prosperity and social equity, for the benefit of current and future generations, leveraged by new business models and responsible consumers. We adopted the CE view in this research.

According to EMF (2015), the circular economy is regenerative and restorative by its design, with the aim of keeping the value and usefulness of components and materials, as long as possible. This concept distinguishes the technical cycle from the biological cycle; as the technical cycle relates to the management of finite material stocks, the use replaces consumption. In this cycle, technical materials are recovered and restored. The biological cycle, on the other hand, incorporates the flows of renewable materials, consumption and renewable (biological) nutrients, which are regenerated, and only occur in this cycle. There are three basic principles for its implementation: (1) designing non-generation of waste; (2) building resilience by encouraging diversity and shifting to renewable energy sources and (3) thinking systemically and in cascades (EMF, 2013).

On the relationship between circular economy and WEEE, Rosa, Sassanelli and Terzi (2019) detected benefits in adopting the circular economy, which they classified according to the triple bottom line:

(1) Economic: overall cost reduction (improved sales and profit margin); reduction of business risks; opening new revenue sources and reduction of products/processes' complexity.

(2) Environmental: compliance with environmental regulations; reduction of environmental impacts; improving resource efficiency and improving supply chain sustainability.

(3) Social: improving brand reputation and value; reaching new markets and countries; enhancing health and safety at the workplace and development of innovative skills and knowledge.

Using waste as a resource is one of its main elements, as well as preserving and extending the use of products. This involves recovery options, such as repair and reuse, and product design that allows extending their life. In addition, corporate reputation is more and more important. For these reasons, private companies are designing reverse logistics structures, thus participating in waste management (Engeland, Belien, Boeck & Jaeger, 2020).

Both circular economy and reverse logistics appreciate WEEE reuse, as it is an appropriate way to deal with the input supply chain, through increasingly available technologies, and to maximize the reuse of waste or part of it after the life cycle. The economic development of these industrial processes creates the opportunity for inserting these materials in a circular economy (Akcil, Agcasulu & Swain, 2019), since its strategies encourage the extension of products' useful life, among other actions (Vanegas, Peeters, Cattrysse, Paolo Tecchio, Ardente, Mathieux, Dewulf & Duflou, 2018).

3. Methodological procedures

This was an exploratory research study with a qualitative approach (Martins & Theóphilo, 2009), and it was based on the study case method (Yin, 2015). We carried out the following stages: definition of the study object; bibliographic survey; documentary survey; technical visit to Reurbi; contacts with experts; creation of research instruments and research execution.

We created five research scripts for the interviews, with open questions. Three of them, which we applied to Reurbi, Sinctronics and Green Eletron, had a common structure: (1) general data on the organization and its representative (the research respondent); (2) reasons to work with end-of-life EEE and WEEE, in addition to information on volumes of material traded and market situation; (3) institutional aspects – norms, taxation and regulations/control and (4) WEEE's sectorial agreement and the resulting opportunities and challenges.

The script applied to Coopernova Cotia Recicla was simpler, with three blocks of questions emphasizing mainly its relationship with Reurbi. Finally, the script applied to the Secretariat of Environment (SMA), in Jacareí, addressed institutional issues related to environmental requirements that Reurbi should comply with, and the potential competition between two initiatives, since the City Hall has a WEEE collection program in the city. Table 2 presents the script used in the interviews.

We interviewed representatives of five organizations: Reurbi; Sinctronics; Green Eletron (manager of reverse logistics); Cooperative Coopernova Cotia Recicla (nongovernmental organization [NGO]) and SMA of the city of Jacareí, as shown in Table 3.

The interviews lasted one hour, on average, and were later recorded and transcribed to facilitate the analysis. We did not get permission to record the interview at SMA in Jacareí.

Blocks	Objectives
I	Characterization – General data about the company and the respondent a. Company; b. Respondent
II	Reasons to act with EEE and WEEE – Volume of EEE and WEEE, market (suppliers/clients) and competition a. Why WEEE? b. Flagship c. Market d. Suppliers How to obtain WEEE and competitors e. Screening/Treatment Decharacterization: Labor, environment, health and occupational safety f. Production capacity (segregated material) g. Buyers; h. Logistics
III	Institutional aspects – norms, regulation/control and taxation a. Regulations, norms and resolutions Licenses; taxation; regulating bodies and controls
IV	Sectorial agreements and aspects related to opportunities

Table 2.
Interviews' script

The names of all respondents were preserved. After transcribing the interviews, we triangulated that information with data from bibliographic and documentary surveys.

4. Results and discussion

4.1 Characterization of EEE reverse remanufacturing chain

The reverse remanufacturing of EEE and WEEE is a set of consecutive steps that make up the reverse flow of this equipment, at the end of its useful life and of its waste from end consumers to the manufacturer/importer/distributor and formal recyclers.

The EEE reverse manufacturing chain has two types of flows from the return by the consumer. The first refers to the flow managed by a system implemented in a local or regional structure, which involves the delivery of EEE in disuse and WEEE, at commercial receiving points. Later, they are sent to the manufacturer, importer and distributor, or to a formal recycler and then to the processing industry, in the case of waste or for other uses in the case of remanufactured equipment. The producer, importer and distributor can also send waste to a formal recycler, who will forward it to the processing industry. In the second flow, EEE and WEEE are received from other collection points, municipal programs, seasonal programs, voluntary receipt and technical assistance and then forwarded to formal or informal recyclers and finally, to the processing industry.

There is a higher incidence of WEEE flow from informal recyclers to the processing industry due to the large number of these recyclers throughout the country.

According to Islam and Huda (2019), this waste has a complex material structure and involves multiple actors in the reverse chain; therefore, identifying the flow of materials within waste management is an essential task, under the holistic concept of a circular economy, a closed loop supply chain and sustainable development.

4.2 Recicladora Urbana in EEE reverse remanufacturing chain

Reurbi collects and decharacterizes end-of-life EEE and WEEE, both from the perspective of business-to-business (B2B) and business-to-consumer (B2C) markets. Reurbi was founded on August 2, 2010, under the corporate name Soatech Comércio e Reciclagem de Eletroeletrônicos Ltda. The company addresses the following activities: (1) collection of WEEE and reception of EEE in disuse or at the end of life; (2) decharacterization of WEEE and remanufacturing of EEE; (3) sale of parts, components and waste and (4) sale and donation to NGOs and charities.

The company is certified by Brazilian System B, is a member of the Ellen MacArthur Foundation and contributes to the circular economy by following the environmental practices of the Sustainability Laboratory (LASSU) of the Polytechnic School of the University of São Paulo (USP). The firm also innovates with the "Remakker" product to assist third sector entities with socio-environmental awareness in using refurbished computers in their technology parks.

As a formal recycler, Reurbi collects or receives EEE (computers, tablets and printers) at the end of their useful life and WEEE from consumers. After remanufacturing, EEE is sent to

Organization	Representative interviewed	Position
REURB	R1	Director founder
ABINEE/Green eletron	R2	Sustainability analyst
Sinctronics	R3	Reverse logistics manager
Coopernova Cotia Recicla	R4	Collectors' supervisor
SMA of Jacareí	R5	Technical advisor

Table 3. Organizations, representatives and interviewees' positions

NGOs, hospitals, call centers and other organizations. In the case of WEEE and parts and components from disassembled EEE, these are sent to industrial companies Sinctronics and Flextronics (plastics recycling), Gerdau and Arcelor Mittal (aluminum and steel recyclers) and GM&CLog (cable recycling).

According to R1, since transport logistics is the factor that most affects the cost of company's operations, when receiving a proposal for collecting end-of-life equipment or WEEE, the first procedure is to carry out a preliminary assessment, considering the distance from the collection point to the disassembly unit in Jacareí. If it is convenient, the firm adopts the following actions: (1) contact the organization interested in the disposal; (2) carry out the inventory; (3) analyze the logistics required for collection and the costs involved and (4) define the amounts to be charged. Saavedra, Barquet, Rozenfeld, Forcellini and Ometto (2013) mention this last action as a major challenge for remanufacturing, due to the difficulty of predicting the volume and timing of return, and the product quality, thus making difficult the remanufacturing operational planning.

Reurbi follows the environmental practices of the LASSU of the Polytechnic School of the USP and presents its remanufactured EEE (mainly computers) as "Remakker" products, which are mainly intended for third sector entities. Also according to R1, these practices are in line with the disassembler's mission, which is to provide companies, organizations and government with conditions for safe, guaranteed and certified compliance with the sustainable management of WEEE, according to the PNRS.

In addition to collection, transportation, control and inventory, segregation and decharacterization of EEE and its waste, the company also does the "sanitization" of data and properties contained in the equipment, according to international standards, which apply to reverse manufacturing and to an environmentally sound disposal of materials after processing. The partial or total reuse of a product can be environmentally effective in terms of impacts eliminated during manufacturing, saving resources and, at the end of its useful life, avoiding discard (Ardente, Peiró, Mathieux & Polverini, 2018).

One of the goals of a circular economy is to improve resource efficiency, which will make the economy less dependent on virgin materials, normally imported, through reduced consumption, reuse and recycling, and minimization of waste streams that leave the economy (Engeland, Belien, Boeck & Jaeger, 2020).

Regarding the flow of reverse remanufacturing of EEE and WEEE at Reurbi, after receiving end-of-life EEE and WEEE, the company checks, lists and weighs the products. Next, they are screened to separate the equipment that can be reused from waste.

Equipment with potential reuse is tested and, if remanufacturing is feasible, is decharacterized for subsequent packaging. After this screening, WEEE is weighed, cataloged, separated by types, disassembled and the different components are separated and sent for decharacterization. At this stage, the reusable parts are inserted in the remanufactured EEE and packaged, weighed, undergo a traceability audit and then stored for subsequent referral to social projects or for resale.

In this process, it is important to define a metrics that can assess the ease of disassembly, thus checking the feasibility of dismantling components without destroying them, so that they can be reused, repaired and remanufactured, according to the circular economy (Vanegas, Peeters, Cattrysse, Paolo Tecchio, Ardente, Mathieux, Dewulf & Duflou, 2018).

One of the problems faced by the company, mentioned by R1, is the illegal collectors or scrap dealers, who compete directly with the business. According to H. K T. Campos (2014b), waste in Brazil generally combines formal actors in regular collection and informal actors in selective collection and waste recovery. The big challenge is to integrate the informal, ensuring appropriate working conditions, increasing collection efficiency and improving waste treatment methods.

Another issue mentioned by R1 is the low value paid per kilogram of parts and components recovered from EEE and its waste (steel, plastics and aluminum). As transport costs from the collection points to the recycling unit are high, it is economically unfeasible for a disassembler to survive operating only in the EEE segment. This is one reason why Reurbi only collects in very specific situations, which depend on the company, on the amount of EEE and WEEE discarded, on the distance and on the required logistics. Another limiting factor for production capacity is EEE's processing time, due to the diversity of parts and components. Mathieux, Recchioni and Ardente (2014) mentioned the need for a standardized method to measure the extraction time of the main product components in order to improve the process.

Reducing disassembly time and related costs will increase the economic feasibility of extending product's useful life and of implementing a circular economy in industrialized regions. Furthermore, disassembly has the potential to increase the recycling yield and purity of precious and nonprecious metals and critical plastics (Vanegas, Peeters, Cattrysse, Paolo Tecchio, Ardente, Mathieux, Dewulf & Duflou, 2018).

R1 also emphasized that one of Reurbi's differentials in the market is the creation of "Remakker" products, especially refurbished notebooks and desktops that return to the remanufactured market, with guarantees similar to those of new products. These are characteristics of a circular economy (Vanegas, Peeters, Cattrysse, Paolo Tecchio, Ardente, Mathieux, Dewulf & Duflou, 2018).

R1 sees the possibility of compensation for the services provided by disassemblers, after signing the sectorial agreement, as an opportunity for the company to achieve a more economically sustainable performance in the EEE segment.

4.3 Interrelationship of Reurbi with the actors of EEE reverse remanufacturing chain

The main suppliers of used equipment and WEEE for Reurbi are banks, industrial companies, schools, medical clinics and domestic users. Among the organizations that receive remanufactured EEE are the Young Apprentices Program, the NGO Recode and Techsoup Brasil.

The Young Apprentices Program is an initiative of a social organization that seeks to train autonomous, aware and connected young people capable of reprogramming the system they live in by using technology. It works in partnership with community centers, libraries and public schools to prepare multipliers through its own methodology that replicate the programs for the final audience. These organizations form a large network of educators, teachers and librarians to promote a new awareness and create opportunities for young Brazilians (Andrade, Santos & Jesus, 2016).

Techsoup Brazil is an initiative of the Telecenter Association for Information and Businesses [ATN], which, in partnership with Techsoup Global Network, helps nonprofit organizations to get technological products and resources for their activities. The program's main task is the donation of software licenses to third sector entities that develop social projects. Techsoup Brazil has partners, like Microsoft, Symantec and Google, which make their products available for donation (Association in Support of Children with Cancer AACC, 2019). Other organizations, such as the Red Cross and the United Nations Educational, Scientific and Cultural Organization (UNESCO), are also among the recipients of EEE remanufactured by Reurbi.

In a broader context, Reurbi also interacts with regulatory and waste management entities, such as the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), which is the Federal government body for environmental license issuing, and the State of São Paulo Environmental Company (CETESB), the agency that issues state environmental licenses.

5. Final remarks

According to the results, the market for remanufactured end-of-life EEE is small. The main recipients are third sector organizations that develop social programs for young apprentices and schools with few financial resources, but concerned about inserting their students in the digital world.

We also observed that disassemblers donate remanufactured EEE to an NGO, in exchange for the indirect benefit of tax deduction of the Tax on Circulation of Goods and Services [ICMS]. The most common market for remanufactured EEE is the resale, after repair, of a piece of equipment that is returned to manufacturers and importers, still during the warranty period, because the customer identified a problem. However, there are still some difficulties, such as the lack of legislation on remanufacturing, a disadvantage that prevents it from being a more structured market in Brazil (Saavedra, Barquet, Rozenfeld, Forcellini & Ometto, 2013).

We observed that there is no consolidated market for parts and components of postconsumption EEE, and disassemblers send these materials to recycling companies. We highlight the case of printed circuit boards, motherboards and video cards that have precious metals in their composition, but due to the volume and investments required for establishing treatment plants in the country, they are exported to countries like Belgium, Germany, South Korea, Japan and China, where companies extract these metals. For H. K T. Campos (2014b), local characteristics of the waste, qualification, cost, availability of local workforce and technological adequacy should be considered when choosing reuse.

The recycling companies Flextronics (plastics), Gerdau and Arcelor Mittal (aluminum and steel) and GM&CLog (cables) receive parts and components from WEEE handled by Reurbi. This fact confirms the study of Ardente, Peiró, Mathieux and Polverini (2018) on the importance of reuse and remanufacturing, through its inclusion in the concept of circular economy, and Moraga, Huysveld, Mathieux, Blengini, Alaerts, Van Acker, Meester and Dewulf (2019) for whom circular economy is a policy for minimizing the burden on the environment and stimulating the economy.

The establishment of an EEE managing company, Green Eletron, in São Paulo, with plans to operate nationwide, is an interesting initiative, as it aims to create a collective system to operate the reverse logistics of small and medium EEE (notebooks, printers, tablets, cell phones and their accessories), for ABINEE member companies and for others that meet PNRS requirements. This initiative is expected to grow and succeed from the signature of EEE's sectorial agreement.

Therefore, we can assume that there is a great market potential related to the reverse logistics of WEEE and end-of-life EEE, as a source of raw material, and which still has to be explored in Brazil, creating new jobs and income. As raw materials are crucial for industrial growth and competitiveness, regarding critical metals, the circular economy is vital for processing, reusing, recycling and recovering sustainable technologies (Akcil, Agcasulu & Swain, 2019).

The results contribute to the dissemination of WEEE recycling and EEE remanufacturing initiatives, which were structured after the implementation of PNRS, in 2010. This shows that both the market (user industries of EEE and consumers of these products) and regulation bodies (federal and state governments) are shaping a distinct management model at national level.

In addition, the prospective approach, which attempts to combine the views of the different actors that interact with Reurbi in the EEE remanufacturing chain, brings to the academic environment the discussion of issues related to PNRS implementation, especially those regarding the sectorial agreement, which are still deeply rooted in the industrial and government environments. Thus, publishing articles that outline the main reflections on the results achieved here can encourage new debates and open opportunities for new studies on PNRS implementation.

As a practical contribution of this research, we mention the dissemination of processes for remanufacturing EEE and for recycling its waste, stimulated by the PNRS and within a circular economy policy. According to Atlason, Giacalone and Parajuly (2017), in a movement towards a more circular business economy, these efforts seek to reduce, narrow and close resource loops. These strategies ensure the wide circulation of resources in society, in the form of products, components and materials.

Considering that Brazil is a great WEEE generator, its proper disposal and that of end-of-life EEE is one of the recurrent topics in the country's sustainability agenda, whether in companies or in academia; thus, it is essential to expand the debate between the actors in the EEE reverse remanufacturing chain and in universities.

Given the challenges and opportunities for the sector, we can also infer that new businesses will emerge. However, this does not mean that they will succeed, as this requires a better assessment of some factors, such as signing of the sectorial agreement and the consolidation of Green Eletron as a manager of EEE reverse logistics in the country, as recommended by the National Industry Confederation (2017).

One limitation of the research is that we only addressed the WEEE reverse remanufacturing chain managed by Reurbi; hence, it is not possible to extend these results to an industrial sector.

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