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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