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ORIGINAL PAPER

Benchmarking of sustainability to assess practices and performances of the management of the end of life cycle of electronic products: a study of Brazilian manufacturing companies

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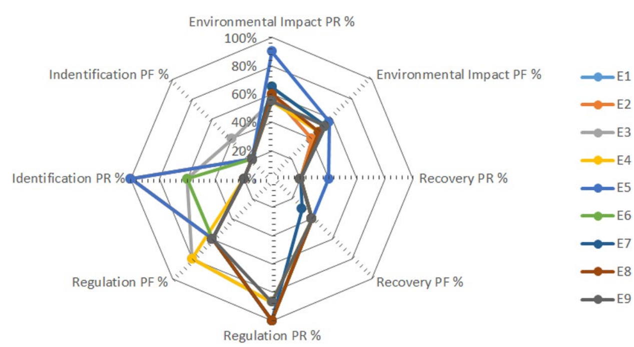
Abstract

The relentless pursuit of lower production costs causes companies to invest in more efficient production systems so that they can remain economically competitive, while the actions focusing on more sustainable operations from an environmental point of view are usually performed to meet the political government regulating environmental control. However, it is common for companies to focus their efforts to minimize the environmental impacts at an early stage of the product life cycle, neglecting sustainability management in the post-use phase. Given the context, this study seeks to develop sustainability indicators that can be used by the electronics industry to assess the level of practice and performance during production that are related to product recovery after the use phase, in order to better understand how companies are acting to reduce the environmental impacts of their products at the end of their life cycle. Initially, critical success factors related to environmental management of the product's end-of-life are obtained. Then, some of those critical success factors are prioritized, giving rise to the indicators of sustainability used in the benchmarking method. Benchmarking was performed in electronics Brazilian companies, and the data was obtained by means of a questionnaire and interviews. It is concluded from the results that the proposed indicators are suitable for measuring the levels of practices and performance of the participant companies in environmental management at the end of the product life cycle as the indicators were able to portray faithfully the reality of each company.

Graphic abstract

Practices and performances in the studied Brazilian companies



Keywords Benchmarking · Electronic products · Sustainable manufacturing · Critical success factors · Indicators · End of life cycle

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Introduction

The increase in industrial production activities has contributed significantly to environmental degradation over the years. Such degradation has led to social awareness, resulting in governments and industries themselves to seek methods to reduce the environmental impacts of industrial production. Many studies propose methods to minimize the waste generated by manufacturing companies, since consumption of products shows a strong tendency to increase (e.g. Tisserant et al. 2017), while product lifespan decreases, caused by factors such as the manufacturer's planned obsolescence (Diegel et al. 2010), or the consumer's desire to have the latest launched products (He and Xu 2014). This form of consumption demands more extraction of raw material from our planet, which are processed in increasing amounts, resulting in more waste (Davidson et al. 2014).

From the point of view of sustainability, the current consumption patterns compromise future generations and assume that natural resources will be available for the next generations (Brundtland 1987). In order to avoid this trend, environmental, economic and social aspects can contribute to mitigate the current process of environmental degradation, moving towards a sustainable development model (Stubbs and Cocklin 2008). It should be highlighted that the actions of companies in the manufacturing sector regarding sustainability involve collection, disassembly, remanufacturing, recycling, correct disposal of waste, among others. These actions are focused directly on the final phase of the product life cycle (Kumar and Putnam 2008).

This context has led to an increasing interest in sustainability in a significant part of the world, including the scientific community, which has sought to develop works on related themes. However, many of those research works generally emphasize wide-ranging environmental reports, leaving specific performance indicators in the background (Roca and Searcy 2012).

Given this scenario, this work proposes a method to diagnose the practices and performances of companies in the electronic products sector, focusing on the final phase of the product life cycle. Electrical and electronic products were considered in this work because they are major contributors to the environmental footprint (Frota Neto et al. 2010) and due to their widespread use and current short lifespan (Pini et al. 2019). The proposed method is based on the Lean Benchmarking methodology (Seibel 2004), with the novelty that Critical Success Factors (CSFs) were used to determine the practices and performances of different manufacturing companies in order to position them comparatively to one another. It should be pointed out that most of previous works focusing on the problem of managing the end-of-life (EOL) of electrical and electronic products apply their studies to a specific type of product (for example, mobile phones, transformers), whereas this work considers different types of electronic products.

The rest of the paper is organized as follows: The next section provides an overview the electronic product sector to highlight the issues around waste generation. "Proposed benchmarking of sustainability method" section emphasizes on the importance of critical success factors and benchmarking of sustainability. "Results and discussion" section elaborates the methods employed, and the following section discusses the results in detail. Finally, "Conclusions" section concludes this research by highlighting the limitations and identifying the areas of future research.

Literature review

Electronic products and the environment

In the last forty years, there has been a significant increase in the number of electronic products such as computers and mobile devices, revolutionizing daily life in the areas of communication, entertainment, and personal productivity. It is estimated that since 1980 more than 900 million desktop and laptop computers, and more than 700 million cathode ray tube screens and flat panel monitors have been sold in the US alone (US EPA 2011). The total market for personal computing devices has grown 11% in the world in the last few years (Meyer and Katz 2016).

The growth of this sector results in concerns about sustainability, since there are many environmental impacts associated with electronic products, such as (a) climate change resulting from energy consumption in their manufacturing processes and use and (b) at the end of life some electronic devices may present risk to the human health and the environment due to the release of heavy metals such as cadmium and lead (Teehan and Kandlikar 2013). A recent report by US Environmental Protection Agency (EPA 2018) points out that 3.09 million tons of consumer electronics goods were produced in 2015, whereas the rate of selected consumer electronics for recycling in 2015 was only 39.8%. Resource recovery from EOL products is becoming increasingly important for the electronics industry (Goggin and Browne 2000). Some of the reasons for recovery of electrical and electronic products include legislation (e.g. Directive EC 2012), trade-in value of reusable products and the recycling potential due to a significant fraction of precious metals. In view of the increased sales of these devices, manufacturers, policymakers, and buyers should seek ways to reduce environmental impacts during and after the life of electronic products by encouraging sustainability, such as using safer materials and reusing the products.

The electronic products considered in this work include LED televisions, smartphones, microwave ovens, conventional telephones, computer monitors, CPUs, CD players, and printed circuit boards (PCBs). Most of these products are composed of plastics, glass, ferrous and non-ferrous metals, and the main components of some of these products are depicted below.

A microwave oven is made up of materials such as plastic, glass, and metals. The electronic boards contain heavy metals such as lead and cadmium, making them the components with the most difficult destination in this product, having to be sent abroad (Luther 2009). PCBs are composed of several layers of silicon and glass fibres interposed by copper and other metals. On the surface soldering points based on lead, tin, and silver are found. For electronic contacts, gold is used (Goodman 2002).

Among the materials used in the central processing unit (CPU), many are toxic such as lead, mercury, arsenic, cadmium, and chromium, as well as plastic components containing brominated flame retardants, halogenated substances, and polyvinyl chloride (PVC), which generates dioxins and furans when incinerated and are also considered toxic (Fisher et al. 2005). Besides these materials, rare and precious metals are also used: gold, silver, platinum, palladium, and gallium (Goodman 2002).

A smartphone is composed on average of 500–1000 components of different materials, being semiconductors and/or precious metals. The most important materials used in smartphones are ceramics, ABS, silver, zinc, nickel, iron, silicon, epoxy, copper, gold, and lead (Singhal 2005). Regarding the battery, the material used is lithium ion (Van Noorden 2014), it is clear that these electronic products generate plenty of wastes which are toxic in nature and simultaneously create major challenges for recycling/reuse.

Environmental assessment of electronic products

This subsection describes previous works that performed environmental assessment of electronic products.

Chancerel et al. (2009) used substance flow analysis (SFA) on a process level as a means to decide about process and product life cycle improvements, as well as to contribute to knowledge about material cycles. They applied the proposed method in a facility in Germany and inferred that after preprocessing (which includes depollution and preshredding), despite the high recovery rates for elements such as iron and copper, only a quarter of gold and palladium ends up in outputs from which precious metals may be recovered. In order to reduce the losses of precious metals, they suggest removing manually the relevant materials (e.g. PCBs) to avoid shredding them.

Katsamaki and Bilalis (2012) proposed a method based on lean thinking to recommend actions to guide redesign proposals for electrical and electronic products seeking to minimize impact to the environment after the end of their useful life. Product design characteristics are examined regarding their relevance to the environment in the EOL stage, and product improvement actions are suggested. They applied the method to a distribution transformer, and some of the suggested redesign actions include use of parts that can be easily separated and reused, use of materials that can be recycled, use high-purity materials.

Shuaib et al. (2014) proposed the Product Sustainability Index, which provides a comprehensive product sustainability assessment (PSA) during its life cycle. They performed sustainability evaluation and comparison of two generations of an electronic product. Harivardhini and Chakrabarti (2016) proposed a model to estimate EOL disassembly effort during early stages of product design. Their method was applied to a CRT monitor disassembly process.

Long et al. (2016) investigated EOL processes, including remanufacturing, reconditioning, repairing, recycling, reusing and disposal of e-waste. They disassembled five mobile phones, and identified the component material, weight, joining method, possibility of re-attachment and damage of disassembly. Based on their findings, they suggested ways to improve design for disassembly, including: (a) use of reusable joining methods, (b) use durable materials that can survive disassembly, and (c) identification of components by means of a QR code. In order to evaluate how the design of batteries can affect the lifespan and potential reuse of PC-tablets and subnotebooks, Peiró et al. (2017) presented a method to analyse the removal of battery packs so as to facilitate their replacement and reuse. Bulach et al. (2018) proposed a recycling route for power electronics modules from electric vehicles and compared their route with car shredders and subsequent post shredder tasks (e.g. sorting). They applied Life Cycle Assessment (LCA), which showed good results for both processes, but the proposed power electronics recycling route enables higher recovery rates for gold, silver and palladium.

Pini et al. (2019) compared the environmental performance, external costs and job creation during the life cycle of new and reused electrical and electronic equipment using LCA. They identified a scenario in which the environmental harm of reconditioned electrical and electronic equipment decreases compared to the new one. Also, their analyses of external costs and social aspects confirm that the preparation for reuse activity allows obtaining a more sustainable product than a new one.

More recently, Bovea et al. (2020) proposed a methodology based on LCA to choose between two end-of-life scenarios (repair & reuse versus replacement) for different electric and electronic equipment categories, considering the type of repair and the equipment's lifespan. They concluded that repair & reuse is environmentally better than replacement. However, for failures such as those related to the motor or PCBs, if they take place in a later product usage, it is better to replace the equipment.

The works mentioned in this subsection, which used methods such as Design for Environment (DFE), Industrial Ecology and LCA, were important regarding the problem of managing the EOL of electrical and electronic products. However, most of those works apply their studies to a specific type of product. Previous studies that considered different types of electronic, did not use CSFs to determine the practices and performances of different companies, identifying indicators that the company should improve to minimize environmental impacts. Previous works that used CSFs to support decision-making by companies regarding minimization of environmental impact will be reviewed in the next subsection.

Critical success factors (CSFs)

The management process and performance evaluation involve a large amount of data, information and various decision alternatives. Therefore, managers must establish priorities and have the data and information necessary for their actions. For this, the concept of critical success factors (CSFs) (Achanga et al. 2006) can be used, which seeks to refine the data and develop an information system that both senior managers and operators can use. Some previous works used CSFs to perform environmental assessment of companies, and those works are referenced below.

Kim and Rhee (2012) examined the impact of CSFs on the performance of Korean companies in the context of green supply chain management (GSCM). They inferred that planning and implementation was the dominant factor regarding company performance, followed by collaboration with partners and integration of infrastructure. They also concluded that increased costs and burdens were obstacles to GCSM in Korea. Chuang and Yang (2014) proposed a model to assess the performance of green manufacturing, and to identify key success factors of its implementation in three companies that manufacture similar products. They concluded that the key success factors for implementing green manufacturing are proportion of non-toxic materials, compliance with eco-ordinances, proportion of biodegradable materials, environmental pollution per product and extent of process pollution.

Luthra et al. (2015) performed a study to assess key success factors behind successful implementation of environment sustainability in Indian automobile industry supply chains. They identified critical success factors and performance measures of GSCM from both the literature and experts from Indian automobile industry. A questionnaire was designed, from which six CSFs (Internal management, Customer management, Regulations, Supplier management, Social and Competitiveness) to implement GSCM for achieving sustainability and four expected performance measures (Economic, Social, Operational and Environmental performances) of GSCM practices. They inferred that the CSF "Competitiveness" is the most important for achieving sustainability in Indian automobile industry. Seth et al. (2016) developed a framework to analyse CSFs and performance measures in a green manufacturing context in the Indian cement industry. Examples of CSFs included Top management, Organisational practices/Culture and Green infrastructure, whereas Quality performance, Green performance and Customer satisfaction are instances of performance measures. They highlighted that top management commitment and human resource management provide significant green benefits. In this line, Jabbour et al. (2017) analysed the relationship between CSFs (Information management, Total involvement of employees, Measurement, Top Management Commitment, Supplier management, Training, Competencies for greener, products & processes) and the adoption of GSCM practices for three focal companies that manufacture automotive batteries in Brazil. They also analysed how human issues can help to increase the effectiveness of CSFs for GSCM strategies. Companies with better attention to the considered CSFs achieved better GSCM and environmental management results. Raut et al. (2017) identified CSFs and assessed their importance with respect to sustainability and applied to companies of the oil and gas sector in India. Some of the CSFs are: Hazardous materials, Cost reduction, Environmental regulations and Training and education. They concluded that "Global Climatic Pressure and Ecological Scarcity of Resources" is the most influential criterion regarding implementation of sustainable practices.

Recently, Jabbour et al. (2018) evaluated whether Industry 4.0 can enhance environmentally sustainable manufacturing and proposed the careful management of CSFs in this context. Some of the proposed CSFs in their work are: Management leadership, organisation, education and training, Data management, Top management support and Communication.

Although the results obtained by the above works showed the usefulness of CSFs toward providing appropriate means for environmental benefits, none of them dealt with companies that manufacture specifically electronic products, and the management of their end of life cycle.

Wittstruck and Teuteberg (2012) carried out a study to identify and analyse success factors toward sustainable supply chain management (SSCM) and performed an empirical study on recycling of electrical and electronics products manufactured by German companies. They inferred that signalling support to sustainable development to partners and stakeholders, information provision and the adoption of appropriate standards are very important preconditions for SSCM success, since they lead to strategy commitment, mutual learning and the establishment of ecological cycles. They did not include in their work the consequences of improved health and safety standards or the increase in employment rights on the performance of companies.

Indicators of sustainability

An indicator is an evaluation mechanism formulated in a measurable basis, being expressed by numbers in associated values and scales (Popova and Sharpanskykh 2010). Indicators can be established as a management method across the company.

Sustainability indicators are measurable aspects to monitor changes in characteristics relevant to the prolongation of human and environmental well-being (Fiksel et al. 2012). The process of developing sustainability indicators has been explored by some authors (e.g. Lehtonen et al. 2016; Mascarenhas et al. 2015). For example, Marshall et al. (2015) attempted to conceptualize and operationalize the concept of supply chain management sustainability practices. Based on the survey of 156 supply chain directors and managers in Ireland, their study developed theoretically sound constructs on four underlying sustainable supply chain management practices: monitoring, implementing systems, new product and process development and strategy redefinition. Roca and Searcy (2012) sought to identify the indicators being used in corporate sustainability reports in Canada, and the indicators were identified based on a content analysis of 94 reports from Canadian companies.

Tahir and Darton (2010) described a method in which a set of indicators is designed from a production operation. The indicators characterize the impact of the operation on the value residing in three domains: environment, economy, and social (Savitz and Weber 2006). From an analysis based on the definition of sustainable development, they verify that these impacts are related to two business perspectives: the efficiency of the resources, and the impartiality with which the benefits are distributed among the interested parties.

Tseng et al. (2016) proposed a method to deal with the linguistic preferences in hierarchical structure of firms' green supply chain (GSC) capability. Data were collected from supply chain networks of electronic manufacturing industry in Taiwan. The authors inferred that the most important capability criteria (which may be considered as indicators) are: environmental costs, strategic alliances, environmental audits of suppliers, environmental standards for suppliers, standardized operational procedures, and environmental department and teams. Also, energy-conservation efforts oriented toward electronic manufacturing firms is the best competitive factor in terms of GSC capabilities.

Schöggl et al. (2016) proposed supply chain sustainability indicators for the European automotive and electronics companies in order to facilitate sustainability assessment. Some of the indicators include: Hazardous substances, Waste management, Occupational Health and Safety, Employee training. The indicators were derived from the literature as well as from interviews involving sustainability and industry experts. They point out that information obtained from the indicators can be used in supplier evaluation, monitoring and selection, procurement, and sustainable product development. However, their work did not relate the proposed indicators to the companies' performance regarding the environment.

Benchmarking

Benchmarking began in the late 1970s as a philosophy that seeks the best practices that guide a company to maximize its performance. The initial milestone was the study by Xerox that sought to compare its operations with those of its competitors (Elmuti and Kathawala 1997).

Organizations began to focus on learning what and how leading companies do to reach the top position. The analysis of the processes, regardless of what they are, offers the opportunity to evaluate the quality of the process and learn lessons that can be adapted to the specific reality of another business or activity (Seibel 2004). The Benchmarking of Sustainability method, proposed in this work, is inspired by the Lean Environmental Benchmarking (LEB) method proposed by Tomelero et al. (2017), which was applied in different companies. The LEB method presents a structure that can be applied to the study of end-of-life management of products, and one addition to the LEB method for such study was the use of CSFs to originate the indicators. The proposed method will be described in the upcoming sections of the paper.

Proposed benchmarking of sustainability method

In this section the steps of the benchmarking of sustainability method are described in detail.

Proposed critical success factors (CSFs)

CSFs were obtained by a comprehensive review of literature regarding the CSFs involved in the end of the life cycle of electronic products.

To begin the search for publications, the terms "managing end-of-life cycle electronic products" were used. 129 papers were obtained, out of which 16 were selected as directly relevant. They deal with the management of the final phase of the life cycle of various electronic products such as cameras, air conditioners, washing machines, computers, telephones, printers and electric heaters, among others. These papers deal with processes of remanufacturing, reconditioning, recycling, reuse and correct waste disposal.

The critical success factors were obtained from the following publications: Tan et al. (2014), Wang and Chen (2012), Babbitt et al. (2011), Kuo (2010), Bandyopadhyay (2010), Iakovou et al. (2009), Xanthopoulos and Iakovou (2009), Johansson and Huge Brodin (2008), Gehin et al. (2008), Duflou et al. (2008), White et al. (2003), Qian and Zhang (2003), Mangun and Thurston (2002), Gable and Shireman (2001), Yu et al. (2000), Goggin and Browne (1998).

30 factors were identified from publications, and citations ranged from two to five times. Observing the factors found, they can be classified into four groups: (a) environmental impact: this group encompasses the factors that deal with items that can generate or prevent environmental impacts; (b) regulation: includes factors related to regulation and incentives by the government; (c) identification: those that suggest that for the best destination of the product in the post-use phase it is important to know the information about the product; and (d) recovery: information that classifies the product as to its recoverability and what the market expects. Table 1 shows the CSFs found in the literature, already grouped.

It is noticed in Table 1 that the number of CSFs obtained was high and, for the application of the method in the companies, it was sought to identify the CSFs that were considered the most relevant by the companies. A description of this procedure is given in Costa (2016), which is based on the application of an initial questionnaire (known as CSF prioritization questionnaire) that was applied to 60 industry professionals and researchers in the

Table 1 Grouped CSFs and their occurrences in the publications considered

Group	Critical success factors (CSFs)	Occurrences in the publications
Environmental impact	Environmental impact due to improper disposal	2
	Hazardous waste	2
	Recovery prediction	3
Regulation	Government regulation	3
	Regulation and standards for recovery	1
	Incentives by the government for recovery	1
Identification	Life of the product	1
	Variability of materials in the product	1
	Identification of components	3
	Identification of the manufacturer	1
	Identification of materials	3
	Identification by make and model	5
	Identification of the quantity of components	1
	Identification of value, time, and quantity	2
Recovery	Weight of recovered material per product	2
	Quantity of recoverable material per product	2
	Time to recover the product	2
	Cost to recover the product	2
	Destruction of part of the product in order to be recovered	2
	Variability of the components	2
	Variability of dimension of the recovered product	1
	Quantity of fixturing elements	1
	Composition of the recovered product	1
	Availability of products to be recovered	2
	Knowledge of the recycling coefficient of the product	2
	Information about the recovered product	1
	Tracking the product life cycle	1
	Information that help product recovery	1
	Prediction of product recovery by a portion of the market	1
	Relation between the product that enters the market and recovered product	1

area of sustainability in Brazil. There were five questions in this first questionnaire, which were the following:

1. In your opinion, what are the critical success factors of the 30 listed below that are essential for the management of the post-use phase of electronic products and components (recovery/reconditioning/recycling/disposal)? Mark T for true or F for false.
2. Mark with *X* only 10 factors that should not be included in this list, as they are not completely relevant to the management of the final phase of the life cycle of electronic products and components.
3. Which other CSF not listed in this list do you consider important for the management of the post-use phase of electronic products and components? Why?
4. On a scale between 1 and 4, fill out how important each CSF is for the post-use management of electronic products and components (1: Not important; 2: Low importance; 3: Important; 4: Highly important).
5. Regarding the relevance for the recovery of electronic products and components, mark according to the scale between 1 and 4 the sets of CSFs (1: Not important; 2: Low importance; 3: Important; 4: Highly important).

After applying the other steps in the method proposed by Costa (2016), five CSFs were considered more relevant by the industry professionals and researchers in the area of sustainability who responded the CSF prioritization questionnaire, which are: (a) identification of materials; (b) environmental impact due to improper disposal; (c) quantity of recoverable material per product; (d) government regulation; (e) hazardous waste. Of these five most relevant CSFs, two are part of the Environmental Impact group, and each of the other three groups (Regulation, Identification, and Recovery) has one of these factors. These five CSFs are used for the development of sustainability indicators, which will be presented in the next subsection.

Indicators

This subsection describes the procedure for the development of the indicators and the structuring of the second questionnaire (known as benchmarking questionnaire), which is used to perform benchmarking.

Steps to obtain and evaluate the indicators

The steps to define the indicators from the selected five CSFs are based on Barbosa (2011). The initial stage for creating and structuring of the indicators consists of finding the variables susceptible to measurement that can be related to the CSFs for the evaluation of the management of the final phase of the life cycle of products of the electronics industry. According to Barbosa (2011), the variables are determined by means of questions, which are elaborated in an attempt to establish quantitative relationships. The questions are placed in the second column of Table 2, whereas variables are shown in the third column of Table 2. For example, for the CSF "Quantity of recoverable material per product" one possible question is "Are there studies aiming at designing products to favour recycling?", for which the following variable susceptible to measurement is proposed: "Existence of studies aiming at designing products that favour recycling". A total of 22 variables were determined.

Subsequently, according to the guidelines used by Barbosa (2011), the objective (fourth column of Table 2) and the justification (fifth column) are defined for each variable. The objective for this variable pointed out previously is "Identify if the company has some project that helps processes and post-use of the product", and the justification is "By means of design studies for reuse/recycling the efficiency of post-use processes can be increased".

Table 2 also shows the type of measure that each indicator should return, which are: quantity, binary (yes or no), description. For the example considered, the measure corresponds to "Existence or not of studies aiming at designing products that favour recycling (Binary)" (eighth column of Table 2).

The final step is the evaluation that attempts to confirm whether the measurable variables are indicators. This evaluation takes place by means of the analysis of the following properties (Soares Jr. and Quintella 2008): relevance, gradation of intensity, univocity, standardization, and traceability. After verifying these properties, all 22 variables related to the CSFs are considered indicators, and they were used in the benchmarking questionnaire to provide data for the benchmarking analysis.

Questionnaire for benchmarking

The benchmarking questionnaire was developed to quantify the level of practices implemented in the production systems of the participant companies, and also their level of performance. Then, they were compared with the indices achieved by other companies in the same sector.

Practice and performance are considered for each group, as shown in Fig. 1. The benchmarking questionnaire's scoring system is based on intervals ranging from 1 to 5, which describe the following scores for each item to be measured:

- Score 1—corresponds to a basic level of practice or performance (20%);
- Score 3—corresponds to an intermediate level of practice or performance (60%);
- Score 5—equals excellence in practice or performance (100%).

Table 2 Some proposed variables and their respective parameters

CSF	Questions	Variables susceptible to measurement	Objective	Justification	Element	Factor	Measure
Environmental impact due to improper disposal	After the use phase, what is the correct destination of the product?	Proper destination of the product after the use phase	Knowing the correct destination of the product after the use phase	Helps achieve the objectives of shared responsibility established by the National Solid Waste Policy	Correct destination	Proper destination of the product after the use phase	Proper destination of the product after the use phase (List)
Hazardous waste	Is there hazardous waste?	Presence of hazardous waste	Check if the product contains hazardous waste to human health or the environment	Check the presence of hazardous waste, quantify and identify seeking the safety of the environment, the employees involved in production, customers, and those involved in recycling/reconditioning processes, in order to minimize risks	Hazardous waste	Hazardous waste in the product	Presence or not of hazardous waste in the product (Binary)
	During the recycling/reconditioning process can hazardous waste be safely separated?	Possibility of safely separating hazardous waste	Check if it is possible to separate the hazardous waste	It is justified by OHSAS 18001 (Occupational Safety and Health)		Separation of hazardous waste safely	Possibility or not to separate hazardous waste safely (Binary)
Quantity of recoverable material per product	The company has program/partnership for recycling/recovery of its products?	Existence of program/partnership for recycling/recovery of products	Identify if the company has some project that helps processes and post-use of the product	By means of design studies for reuse/recycling the efficiency of post-use processes can be increased	Program	Existence of a program/partnership for recycling/recovery of products	Existence or not of a program/partnership for recycling/recovery of products (Binary)
	Are there studies aiming at designing products to favour recycling?	Existence of studies aiming at designing products that favour recycling			Design products	Existence of studies aiming at designing products that favour recycling	Existence or not of studies aiming at designing products that favour recycling (Binary)
Regulation by the government	The environmental policy of the company is known by all employees?	The environmental policy of the company is known by all employees	Check if the environmental management system is spread across the company	The certification became reference over the environmental responsibility of the company, besides becoming a means to disseminate the image, reduce costs, and increase sales	Environmental policy	The environmental policy of the company is known by all employee	The environmental policy of the company is or is not known by all employees (Binary)

Table 2 (continued)

CSF	Questions	Variables susceptible to measurement	Objective	Justification	Element	Factor	Measure
Identification of materials	The company knows the life cycle of the identified materials?	Existence of information about the life cycle of the identified materials in the product	Check if the company has information on the life cycle of the materials	The company has studies of Life Cycle Assessment of the materials that compose the product	Identified materials	Existence of information about the life cycle of the identified materials in the product	Existence or not of information about the life cycle of the identified materials in the product (Binary)

- Scores 2 (40%) and 4 (80%)—refer to intermediate evaluation values of the item.

The results are presented in the next section.

Results and discussion

This section reports the findings of the benchmarking of sustainability method based on the data collected from companies of the industrial pole of Manaus, in northern Brazil, in the electronics sector. In total sixteen companies were approached for this study, but seven of them declined to participate. The companies that participated in the study were large-sized, except for one medium-sized company. Table 3 shows the products manufactured by the nine companies and their number of employees.

Method to apply the benchmarking questionnaire in the companies

The choice of the professionals to answer the benchmarking questionnaire was made according to Seibel (2004): managers, supervisors and engineers who work directly with the products considered were invited. Soon after the companies agreed to participate in the survey, meetings were held to present the proposed research to all those involved, as well as a discussion on sustainability. Then the questionnaire was applied with the 22 indicators. The companies were given adequate time to complete the questionnaire (4-5 months) with follow up by researchers in between to check and clarify any doubts they had.

Analysis of the results

With the data from the nine companies, the benchmarking questionnaire was charted using the Lean Environmental Benchmarking (LEB) method (Tomelero et al. 2017). The companies were referred as $E1$, $E2$, $E3$, $E4$, $E5$, $E6$, $E7$, $E8$, and $E9$.

Analysis of the chart of practices and performance

The chart of practices and performances shown in Fig. 2 places the participant companies based on the general indices of practices and performances obtained by applying the benchmarking of sustainability method. It should be noted that companies $E1$ and $E2$ presented equal general indices of practices and performance.

With the data shown in Fig. 2, companies can be analysed based on their position in the performance and performance chart (Hanson et al. 1994).

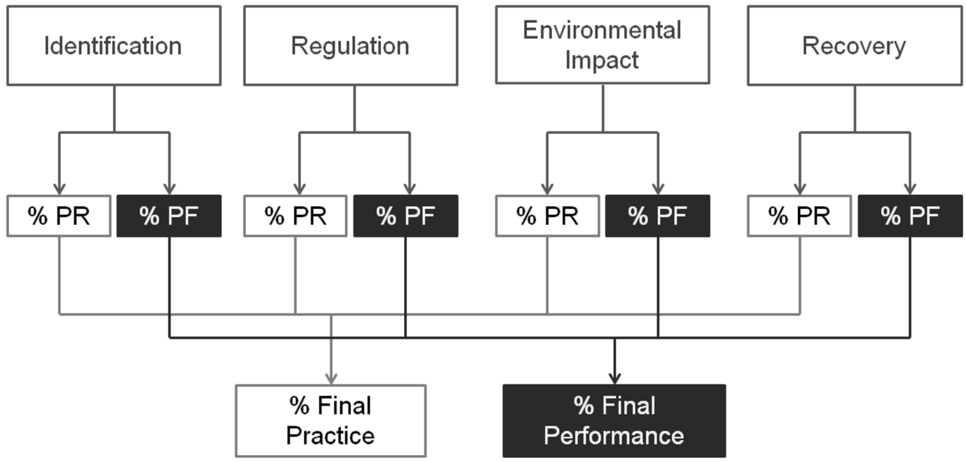


Fig. 1 Determination of the practices and performance of companies

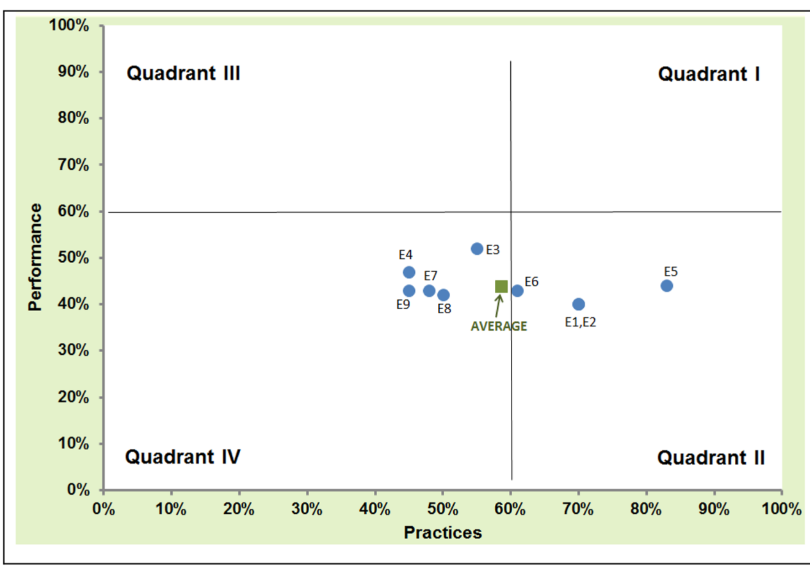
Table 3 Product and number of employees

Products	Number of employees
Printed circuit boards	900
Printed circuit boards	170
CPUs	4100
Televisions	2800
Microwave ovens	1200
Smartphones	2300
Computer Monitors	700
CD players	1500
Conventional telephones	740

The best companies are positioned in quadrant I, while the worst companies are positioned in quadrant IV. Companies in quadrant II are considered “promising” by Hanson et al. (1994), while companies in quadrant III are “vulnerable”.

Companies *E*1, *E*2, *E*5, and *E*6 are considered promising because they have invested in practices but have not yet had return on their investment due to the short time the practices began to be implemented. Company *E*3 has 55% of practice and 52% of performance, being therefore in quadrant IV (worst companies), and the same applies to companies *E*4, *E*7, *E*8, and *E*9.

The average level of practices implemented in the nine electronics companies under study is 59%, and the average performance level is 44%, as shown in Fig. 2. These values would place the group of companies in the worst quadrant, showing that the companies are far from sustainability



Company	Practice	Performance
E1	70%	40%
E2	70%	40%
E3	55%	52%
E4	45%	47%
E5	83%	44%
E6	61%	43%
E7	48%	43%
E8	50%	42%
E9	45%	43%
Average	*59%*	*44%*

Fig. 2 Indices of practices × performances of the participant companies

excellence, which may be threatened in a market that is increasingly committed to environmental concerns.

Analysis based on the radar chart

The values of the practices and performances in the participant companies are shown in Table 4, and the resulting radar chart is illustrated in Fig. 3. The values below 60% for each company are highlighted in italics in Table 4. It can be noticed that companies *E*1 and *E*2 have the same values, whereas *E*6 and *E*7 have only one different value.

The values closer to the centre of the radar chart show weaknesses, indicating where the company has a greater opportunity to carry out improvement actions with more effective results. On the other hand, the points closest to the edges of the graph indicate the best results.

In view of the information contained in the radar chart, it can be verified that the practice indices are higher than the performance indices, with the exception of the Recovery factor, where the performance value is higher than the practice value. The cases in which the average performance is lower than the average practice usually correspond to the situation in which the actions have been implemented for a short time, and require time to be consolidated in order to reflect the performance of the company.

Analysis based on the bar chart

The 22 indicators of practice and performance are shown in Table 5, and Fig. 4 shows the average obtained by all these. It can be verified that the indicators of the variable Recovery ("RE") are the ones that present worse results, while the indicators of the variable Regulation ("RG") are the best evaluated.

In order to identify the causes of the low level of practice and performance of the companies, Tables 6, 7, 8 and 9 show the results of each indicator. The results are presented for the factors environmental impact, recovery, regulation and identification, and the indicators with the worst scores are marked in italics.

The performance of the Environmental Impact factor is shown in Table 6. Practice indicators IA02 (Possibility of redesigning the product to reduce the level of environmental impact) and IA05 (Existence of a program aimed at reducing environmental impact), and performance indicators IA04 (Existence of information on the packaging or product label

Table 4 Values of the practices and performances in the participant companies

	*E*1 (%)	*E*2 (%)	*E*3 (%)	*E*4 (%)	*E*5 (%)	*E*6 (%)	*E*7 (%)	*E*8 (%)	*E*9 (%)	Average (%)
Environmental Impact PR %	60	60	*55*	*55*	90	65	65	60	*55*	63
Environmental Impact PF %	*40*	*40*	*47*	*47*	*57*	*53*	*53*	*47*	*53*	49
Recovery PR %	*20*	*20*	*20*	*20*	*40*	*20*	*20*	*20*	*20*	22
Recovery PF %	*40*	*40*	*40*	*40*	*40*	*40*	*30*	*40*	*40*	39
Regulation PR %	100	100	87	87	100	100	100	100	87	96
Regulation PF %	60	60	80	80	60	60	60	60	60	64
Identification PR %	100	100	60	*20*	100	60	*20*	*20*	*20*	56
Indentification PF %	*20*	*20*	*40*	*20*	*20*	*20*	*20*	*20*	*20*	22

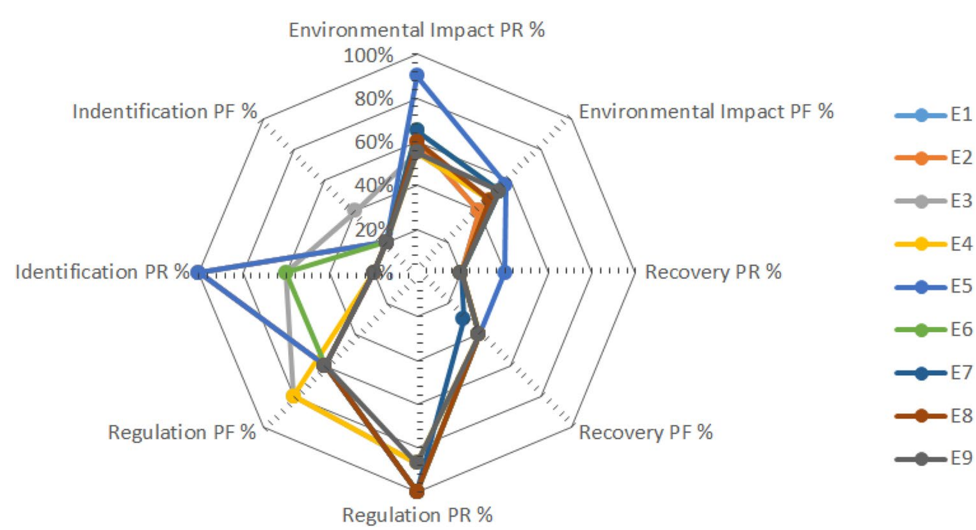


Fig. 3 Radar chart of practices and performances in the participant companies

Table 5 Indicators of practice and performance, and their codes

Factor	Code	Indicator
Environmental Impact	IA01	Possibility of occurring environmental impact due to the improper disposal of the product
	IA02	Possibility of redesigning the product to reduce the level of environmental impact
	IA03	Correct destination of the product after the use phase
	IA04	Existence of information on the packaging or product label on the correct destination after the use phase
	IA05	Existence of a program aimed at reducing environmental impact
	IA06	Presence of hazardous waste
	IA07	Quantity of dangerous waste
	IA08	List of hazardous waste
	IA09	Existence of training for the employee to handle hazardous materials
	IA10	Possibility of separating safely the hazardous waste
Recovery	RE01	Existence of program/partnership for recovery/recycling products
	RE02	Existence of studies for designing products that favour recycling
	RE03	Weight of recoverable material per product
	RE04	Percentage of material recoverable per product
Regulation	RG01	There is regulation by the government
	RG02	Presence of governmental incentives
	RG03	The company has the ISO 14000 standard certification
	RG04	The environmental policy of the company is known by everyone
	RG05	Environmental certifications in the process of being obtained
Identification	ID01	Quantity of material identified per product
	ID02	Existence of information about the life cycle of the materials identified in the product
	ID03	Inform the customer the list with the main materials that compose the product

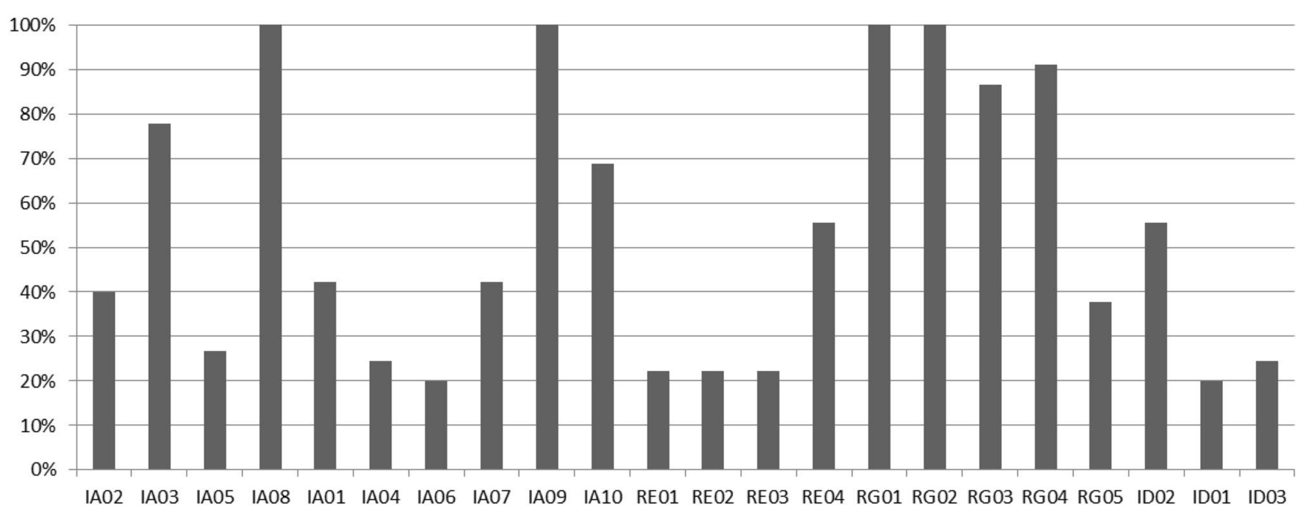


Fig. 4 Bar chart of the indicators for the participant companies

on the correct destination after the use phase), and IA06 (Presence of hazardous waste) had the worst scores in most companies. Thus, these practice and performance indicators should be prioritized by the companies in order to achieve better results regarding environmental impact. For example, in order to reduce the presence of hazardous waste, the design and/or manufacturing processes of the product should be changed by the companies in order to reduce or eliminate the presence of hazardous materials.

The indicators of the factor 'Recovery' in Table 7 with the lowest scores on practices were RE01 (Existence of program/partnership for recovery/recycling products) and RE02

Table 6 Performance of the companies regarding the factor Environmental Impact

Factor	Type	Indicator	Company									Average (%)
			*E*1 (%)	*E*2 (%)	*E*3 (%)	*E*4 (%)	*E*5 (%)	*E*6 (%)	*E*7 (%)	*E*8 (%)	*E*9 (%)	
Environmental impact	PR	*IA02*	20	20	40	20	100	60	20	60	20	40
		IA03	100	100	60	60	100	80	60	60	80	78
		IA05	20	20	20	40	60	20	20	20	20	27
		IA08	100	100	100	100	100	100	100	100	100	100
	PF	IA01	20	20	60	60	20	40	60	60	40	42
		IA04	20	20	20	20	60	20	20	20	20	24
		IA06	20	20	20	20	20	20	20	20	20	20
		IA07	20	20	20	20	60	60	100	20	60	42
		IA09	100	100	100	100	100	100	100	100	100	100
		IA10	60	60	60	60	80	80	80	60	80	69

Table 7 Performance of the companies regarding the factor Recovery

Factor	Type	Indicator	Company									Average (%)
			*E*1 (%)	*E*2 (%)	*E*3 (%)	*E*4 (%)	*E*5 (%)	*E*6 (%)	*E*7 (%)	*E*8 (%)	*E*9 (%)	
Recovery	PR	*RE01*	20	20	20	20	40	20	20	20	20	22
		RE02	20	20	20	20	40	20	20	20	20	22
	PF	*RE03*	20	20	20	20	40	20	20	20	20	22
		RE04	60	60	60	60	40	60	40	60	60	56

Table 8 Performance of the companies regarding the factor Regulation

Factor	Type	Indicator	Company									Average (%)
			*E*1 (%)	*E*2 (%)	*E*3 (%)	*E*4 (%)	*E*5 (%)	*E*6 (%)	*E*7 (%)	*E*8 (%)	*E*9 (%)	
Regulation	PR	RG01	100	100	100	100	100	100	100	100	100	100
		RG02	100	100	100	100	100	100	100	100	100	100
		RG03	100	100	60	60	100	100	100	100	60	87
	PF	RG04	100	100	60	60	100	100	100	100	100	91
		RG05	20	20	100	100	20	20	20	20	20	38

Table 9 Performance of the companies regarding the factor Identification

Factor	Type	Indicator	Company									Average (%)
			*E*1 (%)	*E*2 (%)	*E*3 (%)	*E*4 (%)	*E*5 (%)	*E*6 (%)	*E*7 (%)	*E*8 (%)	*E*9 (%)	
Identification	PR	ID02	100	100	60	20	100	60	20	20	20	56
	PF	*ID01*	20	20	20	20	20	20	20	20	20	20
		ID03	20	20	60	20	20	20	20	20	20	24

(Existence of studies for designing products that favour recycling), and performance indicator RE03 (Weight of recoverable material per product). According to Table 7, the factor Recovery had the worst performance in comparison with the other factors because three of the four indicators scored 1 (the exception was company *E*5, which scored 2). These low scores of Recovery indicators point to the need to carry out actions toward their improvement, which include the implementation of a program for product recovery/recycling, and perform product design that takes recycling into account.

Performance indicator RG05 (Environmental certifications in the process of being obtained) of Table 8 presented the worst value among the indicators of the Regulation factor, while for the other indicators the value was high. This result can be explained by the fact that most of the companies participating in the study already have environmental certifications, and only companies *E*3 and *E*4 are in the process of obtaining the certifications.

According to Table 9, the opportunities for improvement are in performance indicators ID01 (Quantity of material identified per product) and ID03 (Existence of information on the life cycle of the materials identified in the product), which present low scores because the companies do not have the information required by the indicator. In this context, Jabbour et al. (2017) point out the importance of an environmental information management system, and a significant obstacle is the lack of knowledge and information sharing.

Response from the participant companies

A feedback on the analyses of the application of the benchmarking of sustainability method was provided and discussed with the companies except with company *E*7, who chose not to know the result. It was verified that the results were presented in a clear way, since each of them understood correctly where there was a need to intensify the improvement actions. However, these improvements are actions in which the company needs to be careful before implementing, since they may affect the positioning of the product in the market. For example, the packaging may display the materials that compose the product and its correct final destination. From the point of view of label marketing, such change needs market research to determine its viability.

With regard to the indicators with low scores, the following are the responses from companies when asked about what they intend to develop to improve these indicators:

- IA02 (Possibility of redesigning the product to reduce the level of environmental impact), and RE02 (Existence of studies for designing products that favour recycling): These were the indicators that companies show more resistance in developing actions, since the difficulty lies in not having the autonomy to start projects like these. Most of the participant companies are branches of large companies located in the industrial pole, which have their research centres in other places. In this context, Li et al. (2016) point out that product redesign adopting green manufacturing concepts such as disassembly contribute to: (a) making recycling cost effective, and (b) improving green supply chain capabilities, which seeks to reduce material, waste, energy and emissions.
- IA05 (Existence of program to reduce environmental impact), and RE01 (Existence of program/partnership for recovery/recycling products): At least five of the participant companies intend to have programs that meet these indicators. Two companies reported having a reverse logistics program to return the products they manufactured, but when checking the company's website, this information was not available;
- IA04 (Existence of information on the packaging or product label on the correct disposal after the use phase): Some of the participant companies point out that they do not have this information about packaging, but information about the reverse logistics program will soon be available on the companies' website. Reverse logistics is important in the context of green supply chain management (Govindan et al. 2015; Hsu et al. 2016).
- IA06 (Presence of hazardous waste): All the participating companies report using the least harmful materials available on the market;
- RE03 (Weight of recoverable material per product), ID01 (Quantity of material identified per product), and ID03 (Existence of information on the life cycle of materials identified in the product): These are indicators that most companies have shown to have no plan for short-term action, and they argue that this information can be estimated, but do not have it. With regard to indicator ID03, the participant companies reported that they do not have this information. However, during the discussion of the results at least three companies point out that they have the information, but it is not consolidated.

The obtained results are sources of quantitative information for companies regarding practice and performance during the production process, having a direct impact on the final phase of the product life cycle. The benchmarking of sustainability method carried out with the nine companies provides a better knowledge about the company's position in the sustainable context and helps provide a better visualization of the aspects to be improved, enabling the creation of action plans for reducing or eliminating environmental impacts over the product life cycle.

Conclusions

The electronics industry is one of the largest and fastest growing in the world, having produced 50 million tons of electronic and electric waste in 2018 (World Economic Forum 2019). In this context, a method that uses sustainability indicators was proposed in this work to diagnose the level of practices and performances of companies that manufacture electronic products so that processes in the post-use phase of products reduce environmental impacts.

As a general result of the proposed benchmarking of sustainability method, companies are positioned in the worst quadrant (IV), but close to quadrant II (promising companies). Companies *E*1, *E*2, *E*5, and *E*6 were the ones that obtained the best results, classified as promising companies.

Regarding the practice indicators, it was identified that participant companies should carry out actions towards redesigning their products to reduce the environmental impact (e.g. favouring recycling), as well as implementing and improving a program to reduce environmental impact (e.g. considering product recovery/recycling). With regard to the performance indicators, the companies should include information on the packaging or product label about the correct disposal after the use phase, and about the life cycle of materials identified in the product. Also, the companies should seek to eliminate hazardous waste and increase the weight of recoverable material per product.

The results presented by the benchmarking analysis were discussed with the representatives of the companies, who considered them as corresponding to their reality. Thus, the set of indicators was adequate to measure the level of practice and performance during the production process.

Although there are studies on environmental benchmarking applied to electronics recycling products, our study is perhaps the first to provide evidence from the electronics sector on benchmarking of sustainability from a developing country (Brazil). Additionally, the assessment carried out in this paper encompassed the management of the end of life cycle of electronic products. The proposed method can benefit companies to assess and benchmark their sustainability practices. The study, therefore, will not only facilitate the understanding and further research around benchmarking of sustainability but also stimulate research scholars to further apply this in different industrial contexts beyond the electronics sector. This will help research and practitioner communities in better understanding the method and its application as well as the identification of potential challenges that could be encountered in different context and propose solutions to those problems. With better understanding, managers will be able to formulate more effective strategies for the improvement of their operations seeking to reduce environmental impact.

Some critical success factors that could have been considered in the proposed method are the following: (a) information quality and sharing (Luthra et al. 2015), which relates to providing detailed information about the product and its materials and processes to different areas of the company; and (b) supplier management (Jabbour et al. 2017), which involves education and awareness of suppliers regarding environmental issues, carrying out environmental inspections, requirement of an environmental management system and certifications.

As the current study is limited to electronic products, future research could focus on applying the benchmarking of sustainability method in production chains such as metal mechanic and automotive. Moreover, and as this study was limited to Brazilian companies, testing this method in different regions across the globe would also be an interesting area to explore. Finally, it is suggested extending the proposed method to consider economic and social dimensions of sustainability.

References

Achanga P, Shehab E, Roy R, Nelder G (2006) Critical success factors for lean implementation within SMEs. J Manuf Technol Manag 17(4):460–471

Babbitt CW, Williams E, Kahhat R (2011) Institutional disposition and management of end-of-life electronics. Environ Sci Technol 45(12):5366–5372

Bandyopadhyay A (2010) Electronics waste management: Indian practices and guidelines. Int J Energy Environ 1(5):793–804

Barbosa SB (2011) Management of environmental sustainability at the end of the product life cycle: a study based on white goods. Master Thesis in Production Engineering, Universidade Federal de Santa Catarina, Florianopolis, Brazil (**in Portuguese**)

Bovea MD, Ibáñez-Forés V, Pérez-Belis V (2020) Repair vs. replacement: selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. J Environ Manag 254:109679

Brundtland GH (1987) Our common future. World Commission on Environment and Development, Oxford University Press, Oxford

Bulach W, Schüler D, Sellin G, Elwert T, Schmid D, Goldmann D, Buchert M, Kammer U (2018) Electric vehicle recycling 2020: key component power electronics. Waste Manag Res 36(4):311–320

Chancerel P, Meskers CE, Hagelüken C, Rotter VS (2009) Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. J Ind Ecol 13(5):791–810

Chuang SP, Yang CL (2014) Key success factors when implementing a green-manufacturing system. Prod Plan Control 25(11):923–937

Costa LG (2016) Benchmarking of sustainability: a method for diagnosing practices and performances applied to end-of-life management of electronic products. Master Thesis in Mechanical Engineering, Universidade Federal de Santa Catarina, Florianopolis, Brazil (**in Portuguese**)

Davidson DJ, Andrews J, Pauly D (2014) The effort factor: evaluating the increasing marginal impact of resource extraction over time. Glob Environ Change 25:63–68

Diegel O, Singamneni S, Reay S, Withell A (2010) Tools for sustainable product design: additive manufacturing. J Sustain Dev 3(3):68–75

Directive EC (2012) Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment, WEEE. Off J Eur Union L 197:38–71

Duflou JR, Seliger G, Kara S, Umeda Y, Ometto A, Willems B (2008) Efficiency and feasibility of product disassembly: a case-based study. CIRP Ann Manuf Technol 57(2):583–600

Elmuti D, Kathawala Y (1997) An overview of benchmarking process: a tool for continuous improvement and competitive advantage. Benchmarking Qual Manag Technol 4(4):229–243

EPA (2018) Advancing sustainable materials management: 2015 fact sheet, assessing trends in material generation, recycling, composting, combustion with energy recovery and landfilling in the United States, July 2018. https://www.epa.gov/sites/production/files/2018-07/documents/2015_smm_msw_factsheet_07242018_fnl_508_002.pdf. Accessed 09 Aug2018

Fiksel J, Eason T, Frederickson H (2012) A framework for sustainability indicators at EPA. United States Environmental Protection Agency, Washington, USA

Fisher MM, Mark FE, Kingsbury T, Vehlow J and Yamawaki T (2005) Energy recovery in the sustainable recycling of plastics from end-of-life electrical and electronic products. In: Proceedings of the 2005 IEEE international symposium on electronics and the environment, pp 83–92

Frota Neto JQ, Walther G, Bloemhof JA, Van Nunen JA, Spengler T (2010) From closed-loop to sustainable supply chains: the WEEE case. Int J Prod Res 48(15):4463–4481

Gable C, Shireman B (2001) Computer and electronics product stewardship: are we ready for the challenge? Environ Qual Manag 11(1):35–45

Gehin A, Zwolinski P, Brissaud D (2008) A tool to implement sustainable end-of-life strategies in the product development phase. J Clean Prod 16(5):566–576

Goggin K, Browne J (1998) Electronic products recovery-PAWS, a BRITE-EURAM project. Comput Ind 36(1–2):65–74

Goggin K, Browne J (2000) The resource recovery level decision for end-of-life products. Prod Plan Control 11(7):628–640

Goodman P (2002) Current and future uses of gold in electronics. Gold Bulletin 35:21–26

Govindan K, Soleimani H, Kannan D (2015) Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future. Eur J Oper Res 240(3):603–626

Hanson P, Voss C, Blackmon K, Claxton T (1994) Made in Europe: a four nations best practice study. IBM Consulting Group and London Business School, London

Harivardhini S, Chakrabarti A (2016) A new model for estimating end-of-life disassembly effort during early stages of product design. Clean Technol Environ Policy 18(5):1585–1598

He Y, Xu Z (2014) The status and development of treatment techniques of typical waste electrical and electronic equipment in China: a review. Waste Manag Res 32(4):254–269

Hsu CC, Tan KC, Zailani SH (2016) Strategic orientations, sustainable supply chain initiatives, and reverse logistics. Int J Oper Prod Manag 36(1):86–110

Iakovou E, Moussiopoulos N, Xanthopoulos A, Achillas C, Michailidis N, Chatzipanagioti M, Koroneos C, Bouzakis K-D, Kikis V (2009) A methodological framework for end-of-life management of electronic products. Resour Conserv Recycl 53(6):329–339

Jabbour CJC, Mauricio AL, Jabbour AB (2017) Critical success factors and green supply chain management proactivity: shedding light on the human aspects of this relationship based on cases from the Brazilian industry. Prod Plan Control 28(6–8):671–683

Jabbour ABS, Jabbour CJ, Foropon C, Godinho Filho M (2018) When titans meet—can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. Technol Forecast Soc Chang 132:18–25

Johansson G, Huge Brodin M (2008) An analysis of product properties affecting performance of end-of-life systems for electrical and electronics equipment. Manag Environ Qual Int J 19(6):705–717

Katsamaki A, Bilalis N (2012) Lean framework for planning redesign proposals to optimise EOL environmental behaviour in WEEE products. Int J Sustain Eng 5(4):312–324

Kim J, Rhee J (2012) An empirical study on the impact of critical success factors on the balanced scorecard performance in Korean green supply chain management enterprises. Int J Prod Res 50(9):2465–2483

Kumar S, Putnam V (2008) Cradle to cradle: reverse logistics strategies and opportunities across three industry sectors. Int J Prod Econ 115:305–315

Kuo TC (2010) Combination of case-based reasoning and analytical hierarchy process for providing intelligent decision support for product recycling strategies. Expert Syst Appl 37(8):5558–5563

Lehtonen M, Sébastien L, Bauler T (2016) The multiple roles of sustainability indicators in informational governance: between intended use and unanticipated influence. Curr Opin Environ Sustain 18:1–9

Li S, Jayaraman V, Paulraj A, Shang KC (2016) Proactive environmental strategies and performance: role of green supply chain processes and green product design in the Chinese high-tech industry. Int J Prod Res 54(7):2136–2151

Long E, Kokke S, Lundie D, Shaw N, Ijomah W, Kao CC (2016) Technical solutions to improve global sustainable management of waste electrical and electronic equipment (WEEE) in the EU and China. J Remanuf 6(1):1–27

Luther L (2009) Managing electronic waste: issues with exporting e-waste. CRS report for Congress

Luthra S, Garg D, Haleem A (2015) Critical success factors of green supply chain management for achieving sustainability in Indian automobile industry. Prod Plan Control 26(5):339–362

Mangun D, Thurston DL (2002) Incorporating component reuse, remanufacture, and recycle into product portfolio design. IEEE Trans Eng Manag 49(4):479–490

Marshall D, McCarthy L, Heavey C, McGrath P (2015) Environmental and social supply chain management sustainability practices: construct development and measurement. Prod Plan Control 26(8):673–690

Mascarenhas A, Nunes LM, Ramos TB (2015) Selection of sustainability indicators for planning: combining stakeholders' participation and data reduction techniques. J Clean Prod 92:295–307

Meyer DE, Katz JP (2016) Analyzing the environmental impacts of laptop enclosures using screening-level life cycle assessment to support sustainable consumer electronics. J Clean Prod 112(1):369–383

Peiró LT, Ardente F, Mathieux F (2017) Design for disassembly criteria in EU product policies for a more circular economy: a method for analyzing battery packs in PC-tablets and subnotebooks. J Ind Ecol 21(3):731–741

Pini M, Lolli F, Balugani E, Gamberini R, Neri P, Rimini B, Ferrari AM (2019) Preparation for reuse activity of waste electrical and electronic equipment: environmental performance, cost externality and job creation. J Clean Prod 222:77–89

Popova V, Sharpanskykh A (2010) Modeling organizational performance indicators. Inf Syst 35:505–527

Qian X, Zhang HC (2003) An environmentally conscious management model for end-of-life electromechanical products. In: Proceedings of the IEEE international symposium on electronics and the environment, Boston, USA, pp 347–351

Raut RD, Narkhede B, Gardas BB (2017) To identify the critical success factors of sustainable supply chain management practices in the context of oil and gas industries: ISM approach. Renew Sustain Energy Rev 68:33–47

Roca LC, Searcy C (2012) An analysis of indicators disclosed in corporate sustainability reports. J Clean Prod 20(1):103–118

Savitz AW, Weber K (2006) The triple bottom line. Jossey-Bass, San Francisco

Schöggl JP, Fritz M, Baumgartner RJ (2016) Sustainability Assessment in automotive and electronics supply chains—a set of indicators defined in a multi-stakeholder approach. Sustainability 8(11):1185

Seibel S (2004) A benchmarking model based on the world class manufacturing system for evaluating practices and performance of the Brazilian export industry, Doctoral Thesis in Production Engineering, Universidade Federal de Santa Catarina, Florianopolis, Brazil (**in Portuguese**)

Seth D, Shrivastava RL, Shrivastava S (2016) An empirical investigation of critical success factors and performance measures for green manufacturing in cement industry. J Manuf Technol Manag 27(8):1076–1101

Shuaib M, Seevers D, Zhang X, Badurdeen F, Rouch KE, Jawahir IS (2014) Product sustainability index (ProdSI) A metrics-based framework to evaluate the total life cycle sustainability of manufactured products. J Ind Ecol 18(4):491–507

Singhal P (2005) Integrated product policy pilot project: stage I final report—life cycle environmental issues of mobile phones. Nokia, Espoo

Soares J Jr, Quintella RH (2008) Development: an analysis of concepts, measurement and indicators. Braz Admin Rev 5(2):104–124

Stubbs W, Cocklin C (2008) Conceptualizing a "sustainability business model". Organ Environ 21(2):103–127

Tahir AC, Darton RC (2010) Sustainability indicators: using the process analysis method to select indicators for assessing production operations. Chem Eng Trans 21:7–12

Tan Q, Zeng X, Ijomah WL, Zheng L, Li J (2014) Status of end-of-life electronic product remanufacturing in China. J Ind Ecol 18(4):577–587

Teehan P, Kandlikar M (2013) Comparing embodied greenhouse gas emissions of modern computing and electronics products. Environ Sci Technol 47(9):3997–4003

Tisserant A, Pauliuk S, Merciai S, Schmidt J, Fry J, Wood R, Tukker A (2017) Solid waste and the circular economy: a global analysis of waste treatment and waste footprints. J Ind Ecol 21(3):628–640

Tomelero RL, Ferreira JCE, Kumar V, Garza-Reyes JA (2017) A lean environmental benchmarking (LEB) method for the management of cutting tools. Int J Prod Res 55(13):3788–3807

Tseng ML, Tan K, Chiu AS (2016) Identifying the competitive determinants of firms' green supply chain capabilities under uncertainty. Clean Technol Environ Policy 18(5):1247–1262

US EPA (2011) Electronics waste management in the United States through 2009. United States Environmental Protection Agency (EPA) 530-R-11-002. http://www.epa.gov. Accessed 18 June 2017

Van Noorden R (2014) A better battery. Nature 507:26–28

Wang J, Chen M (2012) Management status of end-of-life vehicles and development strategies of used automotive electronic control components recycling industry in China. Waste Manag Res 30(11):1198–1207

White CD, Masanet E, Rosen CM, Beckman SL (2003) Product recovery with some byte: an overview of management challenges and environmental consequences in reverse manufacturing for the computer industry. J Clean Prod 11(4):445–458

Wittstruck D, Teuteberg F (2012) Understanding the success factors of sustainable supply chain management: empirical evidence from the electrics and electronics industry. Corp Soc Responsib Environ Manag 19(3):141–158

World Economic Forum (2019) A new circular vision for electronics time for a global reboot. Switzerland, Geneva

Xanthopoulos A, Iakovou E (2009) On the optimal design of the disassembly and recovery processes. Waste Manag 29(5):1702–1711

Yu Y, Jin K, Zhang HC, Ling FF, Barnes D (2000) A decision-making model for materials management of end-of-life electronic products. J Manuf Syst 19(2):94–107

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