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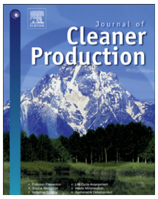

A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil

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ABSTRACT

Electronic waste (e-waste or WEEE) is one of the most critical categories regarding the decision-making for waste management. Brazil is the second major e-waste producer in Americas, after USA, with 1.5 million tones generated annually. However, the absence of adequate system for e-waste reverse logistics are a reality in most of the Brazilian cities. Concerning this hypothesis, we proposed a scenario analysis to support decision-making in e-waste management. This study analyzed the e-waste amount generation, the location of the recycling companies of this segment and the collection routes in the metropolitan region of Rio de Janeiro (MRRJ). Besides, we proposed a set of criteria and indicators to identify the best option for e-waste management. The analysis indicates that Rio de Janeiro is the biggest e-waste producer of the MRRJ, with an amount of approximately 127 ton/day, corresponding to 251 collection points, which represents a high discrepancy in relation to the other municipalities of MRRJ. The findings point out that indicators, such as the Gross Domestic Product (GDP) and Municipal Human Development Index (MHDI), could be used as an alternative for a more accurate analysis for a sustainable urban grid design. This study identified 24 e-waste recycling industries that services the current demand of the MRRJ, most of them concentrated in the central and south portions of the MRRJ, which coincide with the municipalities with the biggest e-waste generation rates. Some hotspots, however, are isolated from the recycling industries, as observed at the MRRJ extremes. In order to provide a better choice for e-waste reverse logistics routes, we proposed 12 indicators, in environmental, economic and social dimensions. Thirty-five hotspots were identified and divided in five main routes according to the recycling industries nearby and the local roads. Urban mining of e-waste seems to be an interesting alternative for secondary raw material recovery, especially in an emerging economy country like Brazil, that consumes huge amounts of electronic devices and demands solutions compatible with environmental law requirements. Hence, this study contributes for a more sustainable development pattern regarding e-waste management in the country, since it reinforces the importance of circularity.

1. Introduction

In the last decades the advances in technology have brought benefits to society at various levels and areas of interest, contributing to progressively connected realities. However, one of the consequences of this modern technological world reflects in an increasingly waste electrical and electronic equipment (e-waste or WEEE)generation, which is the waste generated by devices that demand energy to run. E-waste refers to end-of-life, meaning post-consumed, post-industrialized or post-sold electrical and electronic products. Therefore, most technological products become e-waste at the end of their lifecycle. In the urban context, largely involved with the technological changes, this reality indicates that the e-waste valorization has become a potential strategy not only for reducing the environmental impact and productive costs, but also for optimizing the cycles in the production chain.

E-waste is one of the fastest growing waste streams in the world (European Parliament Briefing, 2015; Awasthi et al., 2018) with an

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annual growth rate ranging from 3% to 5%. The Global E-waste Monitor (Baldé et al., 2017) estimated that Brazil generated 1.5 million ton in 2016, a significant figure when compared with its South American neighboring countries.

The reasons for these impressive numbers lie on many different factors. The dependency of cities on technological advances directly related to the electronics industry, and the increasingly obsolescence among these electronic equipments explain the recently accelerated e-waste generation worldwide (Agrawal et al., 2018). Thus, although the advances in technology have the potential to generate more durable devices adapted to a reverse logistics, these products are intentionally not designed to last long. According to Kumar et al. (2017), the life expectancy of electronic equipment is decreasing, especially in regards of small electronic devices such as cell phones, tablets, and small laptops. While the purchase of such equipment is encouraged, more e-waste is generated.

Particularities of the electronic waste justify the need for a special management of this typology. Since e-waste may derive from a variety of devices (EEA, 2002), its composition can also be diversified, and it is considered to be either hybrid or multi-material. This complexity increases the treatment process costs associated with e-waste management, since different materials demand specific technology and methods for separation and value extraction. Besides, some e-waste contains hazardous elements in their composition, such as heavy metals and Persistent Organic Pollutants (POPs), (Kidee et al., 2013), leading to risks of individual contamination along with potential negative environmental impact (EEA, 2002). An important problem is found especially when these devices are informally treated in the so called “scrap yards”. The use of primitive techniques exposes individuals to the dangers of the e-waste contaminants, which is the case in many developing countries (Ha et al., 2009; Ikhlayel, 2018; Kyere et al., 2018). However, e-waste is also composed of valuable substances as copper, aluminum and gold (Ongondo et al., 2011), as well as critical raw materials (e.g. REE, Nb, Sb, In), which in turn stimulate the market interest in dealing strategically with Urban Mining.

Brazil faces some challenges regarding e-waste management, especially in the metropolitan regions. The lack of reliable information, the informality in the segment, and the absence of an adequate system for e-waste reverse logistics are a reality in most cities (Souza et al., 2016). This is the case of the Metropolitan Region of Rio de Janeiro (MRRJ), the central portion of the state of Rio de Janeiro in the southeast of Brazil with 30 municipalities. Thus, there is an urgency for solutions for e-waste management in MRRJ, mainly due to its e-waste generation and its increasing number of recycling industries.

The objective of this paper is to analyze the scenario in the Brazilian Metropolitan Region of Rio de Janeiro (MRRJ), based on an overview of e-waste generation, collection points and e-waste recycling industries locations. This is achieved using geo-referencing tools that aim to support the decision-making in the region. Additionally, this study is intended to provide a set of criteria and indicators to identify the best options for the urban mining of e-waste in the MRRJ.

Following the introduction, we will present the state-of-the-art circular e-waste management and the Brazilian case. The third part refers to the methodology used, followed by results and discussion in the fourth session. In the fifth session are the conclusions.

2. Background

2.1. Main concepts for a circular e-waste management

In the 20th century, a production model was created especially designed for the benefit of the wealthy countries of the western world. The expensive labor and the abundant natural resources on Earth at that time were the triggers for a take-make-dispose system (or Linear Economy). In such system, the industry could gather resources, make products to be sold, get profit and dispose of anything that was not needed. Thus, reuse and recycling processes both were discouraged not only due to the costs of labor but also because the regulation mechanisms did not charge the producers the externalities of those processes (Ellen MacArthur Foundation, 2013; Sariatli, 2017).

A circular approach on the other hand is based on the closed-loop cycles, a model that fulfills the needs for the next decades to help to avoid the resources exhaustion besides mitigating the impact of significant amounts of left-over waste from the linear economy system. The main principles adopted in the Circular Economy concept consider a “cyclical” logistics which means that products are designed to return to the productive chain by their end-of-life phase (Kirchherr et al., 2017). This is derived from the idea that the materials present in all types of waste (including wastewater and emissions) are viewed as potential input for the consecutive steps of the chain. Therefore, products may be either designed to be easily disassembled and the respective materials separated when discarded or made of materials that are better absorbed by and the environment, or materials that are constantly replaced by natural systems. Moreover, as far as the composition of goods, the target for the industry in a circular model has been switching the focus from “offering a *product* to offering a *service”* (Naor et al., 2018; Doni et al., 2019). This idea prioritizes quality over quantity, as seen in the Linear Economy concept. Along with this approach emerges the upcycling concept, from which both products and services can be enhanced, the materials may return to the chain to generate other products and services with much improved quality (Bridgens et al., 2018). Since quality is highlighted in the production relationship, safety emerges as an important premise: better products/services must be made/work with minimum potentially hazardous substances, considering that the negative impact of these elements on the social, environmental, and economic systems contrast with a closed-loop idea of sustainable business models.

E-waste valorization in a circular model for all economic stages must consider some alternative options for resource value retention, or retention option (RO), as defined by Reike et al. (2018)*: “the conservation of resources closest to their original state, and in the case of finished goods retaining their state or reusing them with a minimum of entropy as to be able to give them consecutive lives”*. It is noteworthy that the resources carry an intrinsic value as opposed to the economic notions of value. Thus, Table 1 shows the options for value retention that can be used in a circular e-waste valorization context.

Considering that the producer is responsible for the costs of disposing defected and obsolete products in a service-based economy (European Commission, 2019), the extension of the life-span of a product for the purpose of generating better services and less costs for the industry is understood as a strategy. It can be performed through cascading systems in the phase of consumption, adopting multiple applications for the good sas well as many more users as possible before discarding. Therefore, strategies such as refusing (R0), reducing (R1), reusing (R2) and repairing (R3) (Kirchherr et al., 2017; Reike et al., 2018) shown in Table 1, can be viewed as potential solutions before the products are considered to be waste.

To determine exactly when a product becomes waste is still uncertain in the literature. Several authors affirm that waste is generated at the moment a user disposes of it, has the intention to discard it, or is requested to discard it (EPA, 1997; EU, 2008). Similarly, for the purposes of this paper, the waste chain starts with

Table 1
Retention options (RO's) applied for a circular e-waste management model.

Retention Option	Definition
R0 Refuse	Refrain from buying; make product redundant (abandoning its function or offering this function with a different product).
R1 Reduce	Use less, use longer; recently: share the use of products; increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
R2 Re-use/Re-sell	Buy second hand (good conditions, fulfils its original function), or find buyer for your non-used produced/possibly some cleaning, minor repairs.
R3 Repair	Making the product work again by repairing or replacing deteriorated parts.
R4 Re-furbish	Restore an old product and bring it up to date.
R5 Re-manufacture	Use parts of discarded product in a new product with the same function.
R6 Re-propose/ Rethink	Buy new product with new function.
R7 Re-cycle	Process materials to obtain the same (high grade) or lower (low grade) quality. Consumer must dispose separately; buy and use secondary materials.
R8 Recover (energy)	Energy production as by-product of waste treatment.
R9 Re-mine	Buy and use secondary materials from landfills.

Source: Adapted from Kirchherr et al. (2017) and Reike et al. (2018)

the disposal being directed to the Reverse Logistics System.

The e-waste valorization is intrinsically related to the management options chosen by the decision-makers aiming to optimize the entire system and also to extract the valuable materials as much as possible from waste. Under the Circular Economy concept, all phases of an electronic product lifecycle must be connected and directed to a return system for e-waste. Fig. 1, herein, shows how the Circular Economy applied to the e-waste management considers both Urban Mining concept and Reverse Logistics, remanufacturing and redesigning as tools for implementing a circular pattern in terms of e-waste streams.

Urban Mining covers a set of operations, such as recovery, analysis, process, recycle, and so on. The goal is to perform the recovery of Secondary Raw Materials (SRM) in the stocks of materials incorporated into cities or in landfills (Serranti et al., 2012). This concept includes the reverse logistics systems for returning discarded products back to the supply chain. Therefore, a circular pattern in this phase should consider strategies for refusing (R0) and reducing (R1) the use of materials and resources for production, as well as reusing (R2) and repairing (R3) equipment, tools and other materials in this process, where the main target is to avoid waste production and negative environmental impacts.

The Circular Economy concept emphasizes the modular design for products so that they can be easily disassembled, and the parts can be separated for repairing or replacement of parts in case of damage or obsolescence. Instead of discarding the entire product, it is possible for the consumer to keep the original product and to deal with the defective part only. Moreover, for the recycling industry, this approach is rather interesting since the modular concept for goods makes it easier to disassemble and to sort out the waste, increasing the optimization of the recycling process.

One other consideration regarding the production phase is related to the hybrid or multi-material goods, that is, those made of different materials (e.g. paper, plastic, metals, etc). The diversity of material contained in the products has a direct impact on the recycling efficiency because each material requires a different recycling process and most of the times, a complex separation. Hence, their total material extraction for recycling can be impaired. This is the case of several electronic products that, because of their hazardous potential, need a special logistics system, apart from the municipal waste chain.

This stage is followed by the products' consumption phase. Here, the consumer is responsible for simply avoiding the use itself (R0) whenever possible, and for maximizing the lifespan of the product through some strategies, such as the ones adopted in the production phase: reducing (R1) the overuse, reusing (R2) or reselling

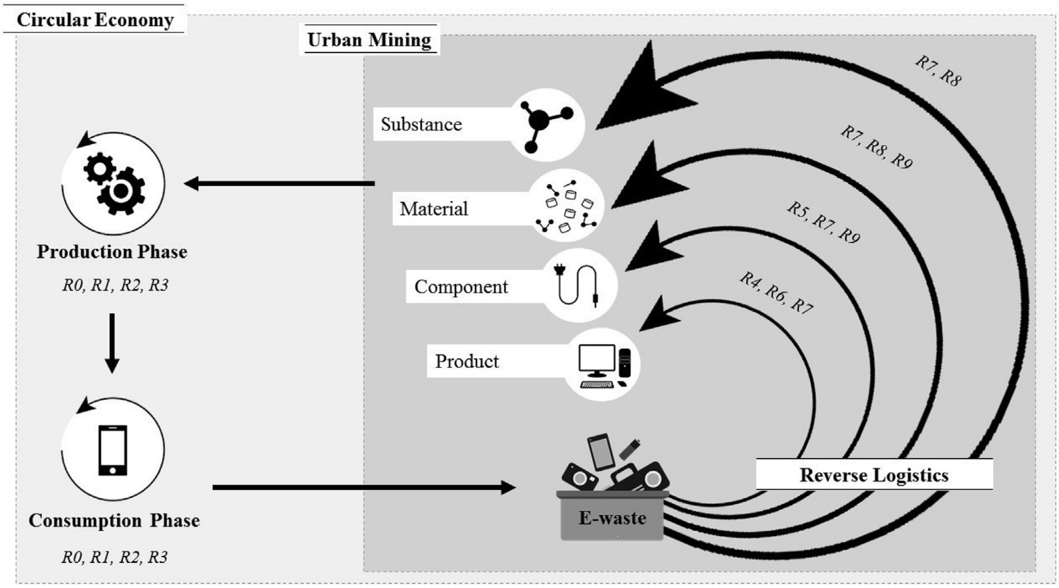

Fig. 1. Circular model for e-waste valorization though urban mining and reverse logistics, modified from Kirchherr et al. (2017), Zeng et al. (2017) and Reike et al. (2018).

while it is still in good functioning state, or repairing (R3) it if damaged. These strategies make it possible to extend both the lifespan and use of the equipment before discarding them as e-waste for reverse logistics.

According to Fig. 1, there are some options for e-waste valorization (Reike et al., 2018) during the Reverse Logistics phase that forward the e-waste for treatment, resulting in four main material state levels for e-waste management (Zeng et al., 2017): product, component, material and substance. Each one of them is related to a specific level of management with specific energy and resources requirements. For example, to extend the product lifespan or reuse requires less energy or fewer resources and the process is for the entire product, while chemical recycling needs higher amounts of energy and resources for the process to be accomplished. In this context, each material state level will require specific conditions and must participate in specific management areas (reverse logistics, remanufacturing, urban mining, recycling, etc).

A product level for Urban Mining is defined by its different components, resulting in products with economic values assigned by the market, i.e. mobile phones, refrigerators, and so on. This is considered as a macro scale and can be obtained through the value retention options of refurbishing (R4), re-proposing (R6) and recycling (R7), since these processes may return with ready-to-sell products. The component level refers to a smaller scale compared with the former, considering examples such as printed circuit boards (PCBs), cathode ray tubes (CRTs) and liquid crystal displays (LCDs) obtained from e-waste dismantling. The options used in Reverse Logistics that can originate resources in a component level for Urban Mining are remanufacturing (R5), recycling (R7) and remine (R9) considering that these components can be used in following steps to produce goods for the market. As a material level, the expected results are uniform matter, such as paper, plastic, metal, and glass. This scale is achieved through certain processes of value retention, for instance: recycling (R7), recovering (R8) and remine (R9). The smallest level, which is the substance scale, refers to a single type of matter consisting of uniform units, as atoms (generating elements) or molecules (originating chemical compounds) (Brunner and Rechberger, 2004).

This microscopic scale can be achieved through the processes that have considerable potential to transform matter, such as recycling (R7) and recovering (R8) as referred in Table 1.

The e-waste treatment results, whether macroscopic or microscopic in the circular model are designed to return to the production chain as inputs and as a new cycle start.

2.2. E-waste management in Brazil

In 2010, the Brazilian Policy on Solid Waste (BPSW), the main Law related to waste management in the country, was enacted by the Federal Law No 12,305 and the Decree No 7404. This document determines that e-waste is one of the six categories with priority for the management, which must be established through the implementation of reverse logistics systems (RLS) with procedures such as collection, transportation, packaging and secondary logistics for the environmental disposal of waste. Under this regulation, producers, importers, retailers and distributors must implement the RLS, as their shared obligation responsibility, while the consumers, on the other hand, are responsible for the return of post-used products.

According to the BPSW, the RLS maybe implemented and made operational through regulations, sectoral agreements (SA), and the commitment terms (CT). The regulations refer to the decrees issued by the Executive power. The technical and the economic feasibility studies, as well as the public consultations for the establishment of SLRs, must be previously carried out. The SA are acts signed between the government and the producers, importers, distributors or traders, in order to implement a model for RLS considering shared responsibility for the life cycle of products for each player of the reverse supply chain (BRAZILa). This document (SA) was recently signed on October 31, 2019, presenting the deadlines by 2025 regarding a collection rate at 17% of the products put on market in 2018. The Decree No 7404 (BRAZILb) states that CT should be performed in the absence of specific regulations or SA in the referred state, or even if the targets set are more restrictive than those contained in the SA and regulations.

Regarding the state of Rio de Janeiro, the implementation of the RLS is mandatory by the state Law No. 6.805/2014 (Rio de Janeiro, 2014), which establishes the state solid waste policy. According to its state solid waste plan, the policy should focus on actions aimed at increasing the scope of selective collection, implementation of reverse logistics and to the shared responsibility for the product life cycle, thereby reducing the amount to be disposed of in landfills.

3. Methodology

In order to identify the main drivers of e-waste management in Rio de Janeiro state (Brazil), under the circular economy approach, we have proposed a bibliographical review and a case study with geo-referenced image analysis. The study was based on a diagnosis of e-waste management in the Metropolitan Region of Rio de Janeiro (MRRJ), considering an estimate of the e-waste generation amount, followed by a discussion about the number of the e-waste collection points needed according to the literature, as well as the identification and geo-referencing of the current recycling industries that supplies the demand in the MRRJ. The specific methodology used in this study is summarized in the diagram of Fig. 2 and presented in detail hereafter.

3.1. Case study and scenario analysis

To accomplish the case study of the MRRJ, the study identified different routes between the main generation hotspots and the recycling companies. The selection of the best routes for e-waste valorization through Reverse Logistics and Urban Mining was done with the support of criteria and indicators proposed for this scenario. The Fig. 3 shows the map of MRRJ with its 30 municipalities.

3.1.1. E-waste generation in the MRRJ

The methodology applied for estimating the amount of e-waste generated in the MRRJ was first based on the identification of the municipalities that are part of this region. The number of inhabitants of each municipality was obtained by the last Brazilian demographic census (IBGE, 2010). According to Baldé et al. (2017), Brazil generated 7.4 kg/inh in 2016. To obtain the classification of municipalities according to the generation of e-waste, this amount was multiplied by the population of each municipality. This method for estimating e-waste generation was based on the sales rate and the lifespan of electronic products, which do not consider the particularities of this region. Thus, these numbers were compared with the values of the Gross Domestic Product (GDP) and the Municipal Human Development Index (MHDI, or IDHM, in Portuguese). The former reflects the economic aspects of each municipality and the latter considers criteria such as longevity, education and income levels, varying from 0 to 1. The closest to 1, the most developed, according to the index. Both variables were obtained from the Brazilian Institute of Geography and Statistics - IBGE (2010).

3.1.2. E-waste collection points in the MRRJ

Through bibliographic research, we sought methodologies to quantify the necessary number of collection points, or Voluntary

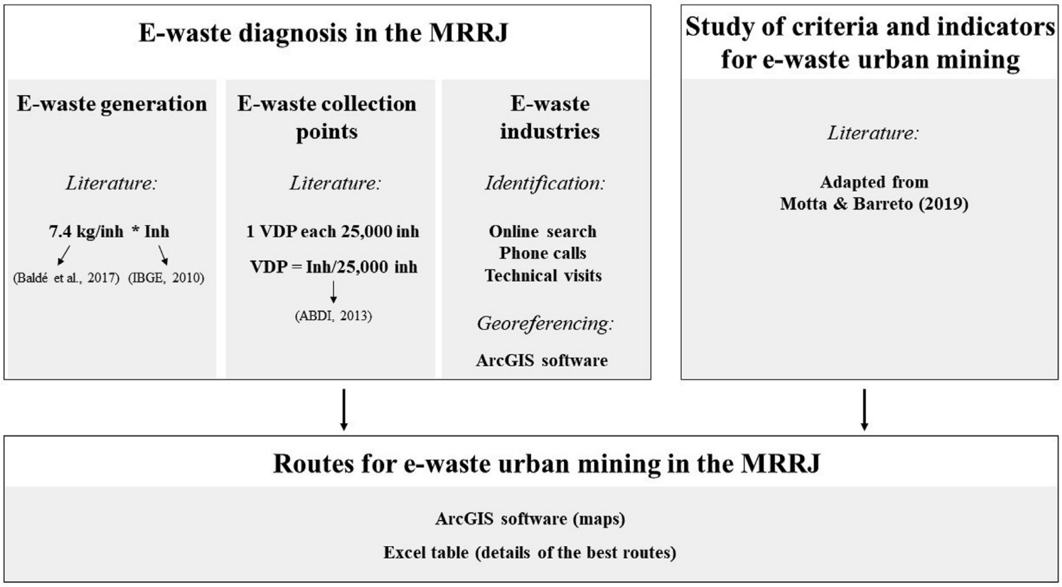

Fig. 2. Scheme of the methodology adopted in this study.

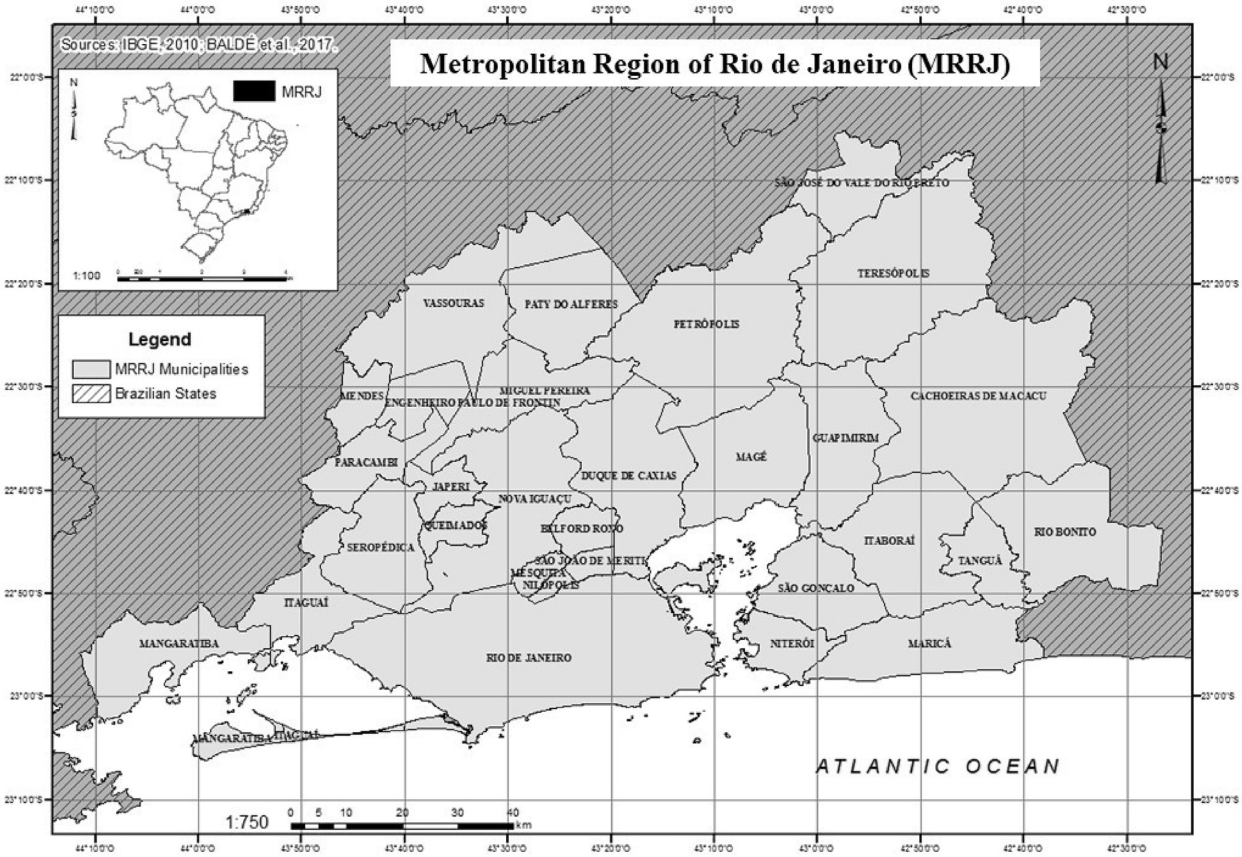

Fig. 3. Political map of MRRJ and its 30 municipalities.

Delivery Points (VDPs), for e-waste. According to the Brazilian Agency for Industrial Development (ABDI, 2013), for Reverse Logistics purposes in the country, it is estimated that one VDP is required for every 25,000 inhabitants. This search allowed for the calculation of, within the sample population, how many VDPs each municipality of the MRRJ should install in order to contribute to reverse logistics.

Finally, it was verified that if the method of quantification of these collection points was used adequately, it would correspond to more realistic numbers of e-waste generation in the municipalities of the MRRJ. Therefore, the use of other variables, such as MHDI, area and population, could provide a more coherent annual data for the amount of waste, by mass, per VDP. This analysis is relevant in assisting decision makers and companies involved in the logistics of both the allocation and implementation of such VDPs, as well as their maintenance and collection of waste disposed of in them.

3.1.3. *E-waste recycling industries in the MRRJ*

In this phase, it was considered the number of recycling industries that comply with the demands of the MRRJ for e-waste handling and treatment, regardless of whether or not they are located within MRRJ. It is important to highlight that, for the purpose of this paper, “recycling industry” means any type of industry that deals with or processes e-waste at any phase of the management. Therefore, the companies that perform storage, collection, sorting, processing, refurbishing, remanufacturing, recycling, among others, were considered.

The companies were identified through the search of service providers and industries that operate in the different segments of the circular economy of electronic waste, starting with online search engines. After defining the first contacts, we used references from other partners that act in the reverse logistics of electronic waste in the research area. For this search, keywords such as: “VDP [Voluntary Delivery Points]”, “delivery points”, “electronic waste”, “discard”, “recycle”, “e-waste”, “electronic”, “batteries”, “bulbs” and the like were used. Some institutions were contacted by telephone to collect registration information. The companies were then classified based on the report of the activities developed, either found on their respective websites or obtained through telephone calls, and the descriptions of the activities related to the CNAE (Brazilian code for economic activities). The evaluation of the raw database was performed by reviewing the general information released in the spreadsheet regarding the identification of e-waste recycling companies, validation of information consistency, rectification of possible inconsistencies and duplicate data, and checking of the economic activity though in situ verification to confront with the CNAE description and the evidence of the processes actually developed by the company. The location of these companies was georeferenced on a map, obtained by Google Earth and the software ArcGIS, and compared with information on the e-waste generation in each municipality of the MRRJ.

3.2. *Best routes for e-waste management*

3.2.1. *Proposal of criteria and indicators for e-waste management*

The criteria and indicators were thought of as guidelines to indicate the best routes for e-waste management and valorization. These topics were built upon the Sustainability concept, considering environmental, economic, and social aspects. The methodology adopted for this phase was based on the literature review and then organized in an Excel datasheet.

The indicators selection was adapted from the methodology used by Motta and Barreto (2019), with the adoption of three premises: a) be applicable to e-waste management; b) be measurable using primary or secondary data; c) be objective and easy to understand for information gathering. Primary data means data obtained directly during the search, while secondary data come from the literature.

3.2.2. *Best routes for Urban mining of e-waste in the MRRJ*

The possible routes for the urban mining of e-waste were established by the development of a map with ArcGIS software, containing information about the estimate of e-waste generated, the main streets and urban roads from the hotspots of generation (the hotspots considered as e-waste generation higher than 40 kg/day for each census tract, one of the units used for this study) to the recycling industries. The criteria and indicators proposed in Section 3.2 (i) were used to determine the routes that optimize the e-waste flux and the reverse logistics in the MRRJ. The best routes were then organized in a table considering the main hotspots as well as the suggested recycling industry for each hotspot.

4. Results and discussion

The transition from a Linear to a Circular Economy includes a set of adaptations that may require resources according to the size or the complexity of the productive sector, the geographical area, and or the number of agents involved. Understanding waste as nutrients for industry justifies the potential for closing the loop as a profitable and strategic business model. It also creates a technological approach for this goal. Table 2 compares Linear and Circular Economy by summarizing their main aspects, presenting problems and obstacles of the former, and opportunities found in the latter for the new context of the human development in the planet. Table 2 presents the main points of each stage in Linear and Circular Economy.

As presented in Table 2, the circular economy accomplishes the sustainability criteria since the lower energy and material requirements are at the starting point, re-make and re-design the products and processes. After the lifespan in the final step, the material recycling alternatives are regarded as end-of-line solutions with higher energy and material consumption. The comparison of circular and linear approaches summarizes the main challenges to be considered in the new and sustainable business models.

4.1. *E-waste scenario in the MRRJ*

4.1.1. *E-waste generation in the MRRJ*

Although there are few references regarding e-waste management in Brazil, Souza et al. (2019) and Motta and Barreto (2019) emphasizes specificities of e-waste management and proposed complimentary methods for e-waste management evaluation. From the evaluation of e-waste generation, it is possible to identify the bottlenecks, support public policies and improve the management procedures.

The analysis of GDP and MHDI indicators along with the methodology adopted for the estimation of e-waste generation proposed by Baldé et al. (2017), is justified in an attempt to approximate this amount to a more realistic one, since both GDP and MHDI indicators consider the social and economic aspects of the local population.

Table 3 presents the e-waste generation in ton per day, of the 10 biggest municipalities in the MRRJ in terms of e-waste generation estimated, as well as the population, GDP values and MHDI.

It can be observed that Rio de Janeiro is the largest municipality of MRRJ in regards of population, e-waste generated and GDP, but not related to MHDI, following Niterói. Despite the MHDI value, the information in Table 3 clearly indicates that Rio de Janeiro can be considered the biggest e-waste producer of the MRRJ.

Due to its high discrepancy in relation to the other values, for the analysis of the patterns between the three variables (population, GDP and MHDI), the data for Rio de Janeiro were disregarded, and a graph listing the other municipalities was prepared (Fig. 4). This analysis aims to corroborate with future determination of correlations that may influence the generation of e-waste in Brazilian municipalities and may be considered for other future studies for the formulation of equations to quantify their generation more adequately, considering the Brazilian reality.

Table 2
Main problems of the linear economy and the opportunities found in the circular economy model.

Problems of the Linear Economy		
Take	Make	Dispose
RESOURCES	*PRODUCTION*	*POS-CONSUMPTION*
Depletion of primary natural and nonrenewable resources	Loss of value of potential resources from byproducts	Environmental/economic/social impacts from disposal
Environmental and social impacts of primary resources extraction	Products are not designed to disassembling or to return to the productive chain	Environmental/economic/social impacts from downcycling (loss of value)
	Production systems are not connected with end-of-chain systems	Loss of value from misuse (underuse)
	Impacts of production systems	
	Massive production and low quality	
Opportunities of the Circular Economy		
(Re)Make/Design	**Use**	**Return**
RESOURCES	*CONSUMPTION*	*DISPOSAL*
Products designed for disassembling (monomaterial and modular design)	Refuse (R0) - Reduce (R1) - Reuse (R2) - Repair (R3)	Recovering material from waste (SRM) - Waste to Resources (WtR)
Priorization for bio-based materials (easier for nature's assimilation)	Modular products — to allow the consumer self-repair	Recovering energy from waste — Waste to Energy (WtE)
Products free from toxic components	Cascading consumption	Closing the loop as a profitable business
Alternative and renewable energy sources		Industry 4.0 for traceability and reliability
Services as the new products (products with longer life span as more profitable for industry)		Upcycling - Increase product/service quality, cost and/or efficiency from a cycle to the other
Connected systems based on Industrial Ecology and Industrial Metabolism		Avoid exploitation of natural resources by SRM recovering

From Fig. 4, it is possible to infer that both population and GDP present a certain pattern and are directly correlated in the municipalities of MRRJ. Similar results were also observed by Kumar et al. (2017), who states that e-waste generation of a country is directly correlated to its GDP. The MHDI curve shows greater variations in relation to the other two variables, though generally higher in the municipalities with larger population and higher GDP.

This trend is aligned with the following expectations: the richer the municipality in question, the higher its MHDI values tend to be, given it has more resources to invest in education, health, sanitation and extended life expectancy coupled with quality of life. Municipalities with higher resources tend to generate more e-waste as well because the use of electronic products is usually higher in places with larger income. Thus, although quantified in numbers in the present study, it is also expected that municipalities with higher GDP and higher MHDI present larger amounts of e-waste generated. These results are consonant with the literature, considering that the population size may not have a significant impact on e-waste generation (Kumar et al., 2017), and consequently, highlight the influence of other social and economic-related indicators.

4.1.2. *E-waste collection points in the MRRJ*

Some municipalities in the MRRJ already have VDPs though in isolated ways. It is the result of the initiative of some municipal governments and the private sector, as a formal Reverse Logistics System (RLS) was only officially formalized recently by a Sectoral Agreement signed on 31 October 2019 and the Decree No 10,240 (BRAZIL) enacted on 12 February 2020. The decree establishes some remarkable aspects such as de definition of: (i) *management entity* as a legal entity constituted by manufacturers and importers or associations of manufacturers and importers of electronic products, which meets the technical management requirements, with the objective of structuring, implementing and operating the e-waste reverse logistics system; (ii) *receiving, delivery or collection point* as fixed or mobile locations for receiving and temporarily storing electronic products discarded by consumers; (iii) defines collection and destination as obligations to be fulfilled by the fifth year of implementation of the e-waste reverse logistics system, and (iv) the number of Brazilian cities to be attended by the implementation of the e-waste reverse logistics systems as 24 (0,43%) cities in the first year, until 400 (7,18%) cities in the fifth year.

The number of collection points or Voluntary Delivery Points (VDPs) in Brazil can be estimated by using the literature (ABDI,

Table 3
E-waste generation, population, GDP and MHDI in the ten biggest e-waste producers of MRRJ.

Municipality	E-waste generation (ton/day)	Population (inhabitants)	GDP (million $)	MHDI
Rio de Janeiro	127.4	6,283,486	49.96	0.799
São Gonçalo	20.2	997,950	2.,48	0.739
Duque de Caxias	17.3	854,077	5.55	0.711
Nova Iguaçu	16.1	795,411	2.43	0.713
Niterói	9.8	484,918	3.02	0.837
Belford Roxo	9.5	468,910	1.06	0.684
São João de Meriti	9.3	458,403	1.20	0.719
Petrópolis	6.0	294,813	1.74	0.745
Magé	4.6	226,212	0.57	0.709
Itaboraí	4.4	217,606	0.58	0.693

Source: Based on IBGE (2010) and BALDÉ et al. (2017)

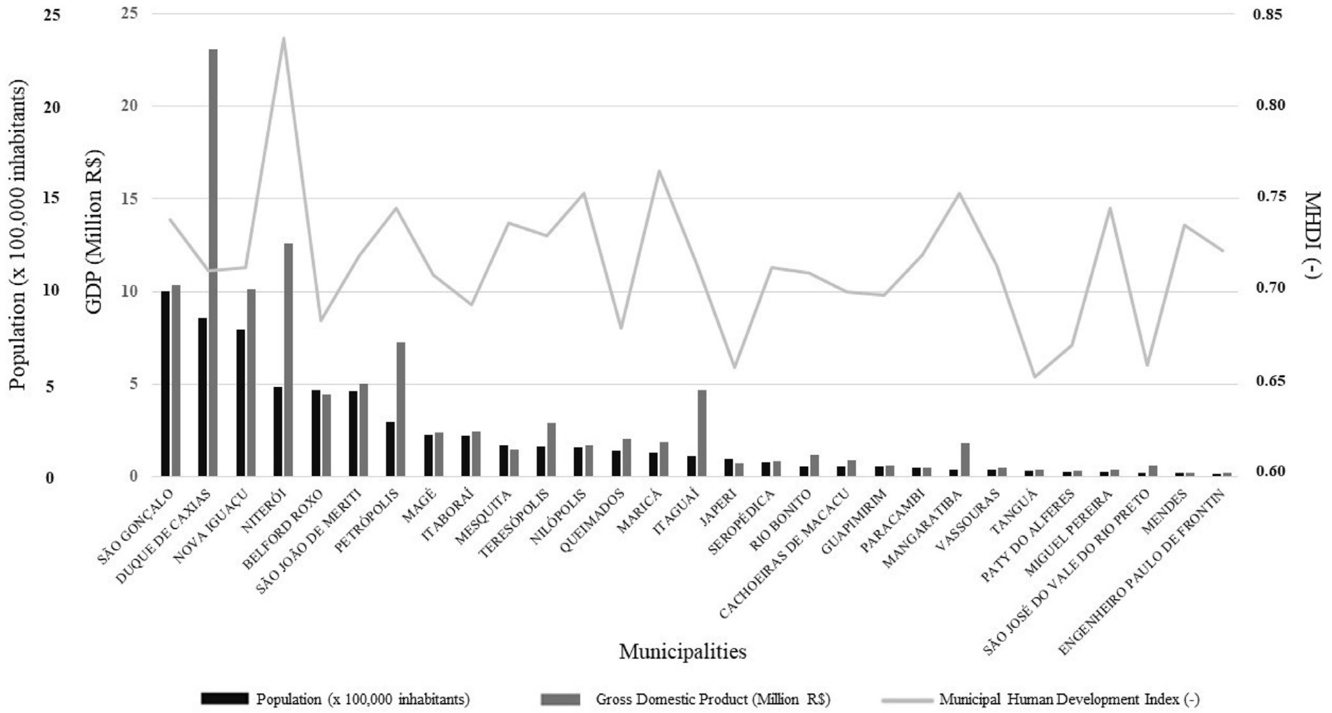

Fig. 4. Patterns of population, GDP and MHDI in the municipalities of the MRRJ, except Rio de Janeiro, for its high discrepancy with other municipalitiesSource: Based on IBGE (2010).

2013) based on the population. The proportion is calculated as one VDP for each 25,000 inhabitants, which corresponds to approximately one VDP unit with storage capacity of 0.5 ton per day. Table 4 presents the amount of VDPs estimated for each municipality. It compares these numbers with the municipality areas in order to obtain an approximate distribution of these units throughout the cities.

Table 4 shows that Rio de Janeiro, as the largest e-waste generator with the highest population index, has a prominent value for the units needed for collection points: 251, while the nearest municipality in the sequence, São Gonçalo needs 40 VDPs, about six times lower. However, considering the values of the municipal areas, it can be observed that the distances from one VDP to another are long, both in Rio de Janeiro and São Gonçalo, the two highest values of these collection points located in the studied area. Bringhenti (2004) estimates that such points should not exceed 0.5 km from that of the consumers not inhibited them from contributing to reverse logistics. Similarly, in municipalities with significant distances from VDPs, the scope of reverse logistics tends to be insufficient and ineffective, and an alternative form of e-waste collection should be considered, such as municipal take-back systems as an example. One other possibility includes e-waste collection campaigns highlighted in the current scenario of e-waste management, due to lower expenses of installation, maintenance, and proper collection in the VDPs. In addition, the campaigns can provide greater visibility and reach larger groups of people, contributing to improve the e-waste collection rates.

4.1.3. E-waste recycling industries in the MRRJ

This study identified 24 e-waste recycling industries that service the current demand of the MRRJ. Fig. 5 shows the distribution map of these companies compared with the daily e-waste generation average in each municipality. The values adopted for this generation were given on a daily scale in order to provide adequate information focused on the collection of this material.

Fig. 5also shows the concentration of e-waste companies in the central and south sections of the MRRJ, which coincide with the municipalities having the highest e-waste generation rates. The population density in this region also contributes to a higher e-waste generation. Nevertheless, this generation volume does not correspond to a representative collection rate, due to the lack of efficient routes or proper disposal channels.

Both pieces of information indicate the trend for the market configuration of e-waste urban mining and the possible main routes for the reverse logistics. The municipality of Rio de Janeiro generates on average more than a hundred tons a day. This justifies the concentration of e-waste recycling companies and the urgency for a Reverse Logistics System, considering the environmental impacts associated with the mismanagement of generated e-waste. Nevertheless, many of such higher generation points are isolated from the recycling industries, as observed at the MRRJ extremes. The study of the installation of new recycling companies to supply these areas becomes fundamental for the optimization of the e-waste valuation chain. It is noteworthy that some recycling companies in São Paulo, neighbor state from Rio de Janeiro, currently service the MRRJ region.

4.2. Best routes for e-waste management in the MRRJ

4.2.1. Criteria and indicators

Establishing the 12 indicators was based on four main criteria: the *distances* between the hotspots of e-waste generation and the recycling industries; the *proximity* between two or more hotspots; the *type of recycling industry*, in other words, the category of e-waste accepted by these companies; and the *local context* of the hotspots. Table 5 shows the description and dimension of each indicator for a circular e-waste management in the MRRJ.

The indicators shown in Table 5 suggest that the shorter the

Table 4
E-waste collection points (VDPs) in the MRRJ.

Municipality	E-waste generation (ton/day)	Population (inhabitants)	VDP (units)	Municipality Area (km^2)	Coverage km^2/VDP
Rio de Janeiro	127.4	6,283,486	251	1200	5
São Gonçalo	20.2	997,950	40	248	6
Duque de Caxias	17.3	854,077	34	468	14
Nova Iguaçu	16.1	795,411	32	521	16
Niterói	9.8	484,918	19	134	7
Belford Roxo	9.5	468,910	19	78	4
São João de Meriti	9.3	458,403	18	35	2
Petrópolis	6.0	294,813	12	796	67
Magé	4.6	226,212	9	389	43
Itaboraí	4.4	217,606	9	431	49
Mesquita	3.4	168,301	7	39	6
Teresópolis	3.3	163,356	7	771	118
Nilópolis	3.2	157,296	6	19	3
Queimados	2.8	137,760	6	76	14
Maricá	2.6	127,315	5	363	71
Itaguaí	2.2	108,937	4	276	63
Japeri	1.9	93,252	4	82	22
Seropédica	1.6	77,495	3	284	92
Rio Bonito	1.1	55,004	2	457	208
Cachoeiras de Macacu	1.1	54,195	2	954	440
Guapimirim	1.0	51,402	2	361	176
Paracambi	0.9	46,011	2	180	98
Mangaratiba	0.7	36,321	1	356	245
Vassouras	0.7	34,230	1	538	393
Tanguá	0.6	30,482	1	146	119
Paty do Alferes	0.5	26,253	1	319	304
Miguel Pereira	0.5	24,567	1	289	294
São José do Vale do Rio Preto	0.4	20,186	1	221	273
Mendes	0.4	17,916	1	97	135
Engenheiro Paulo de Frontin	0.3	13,180	1	133	252

Source: Based on IBGE (2010), ABDI (2013) and BALDÉ et al. (2017)

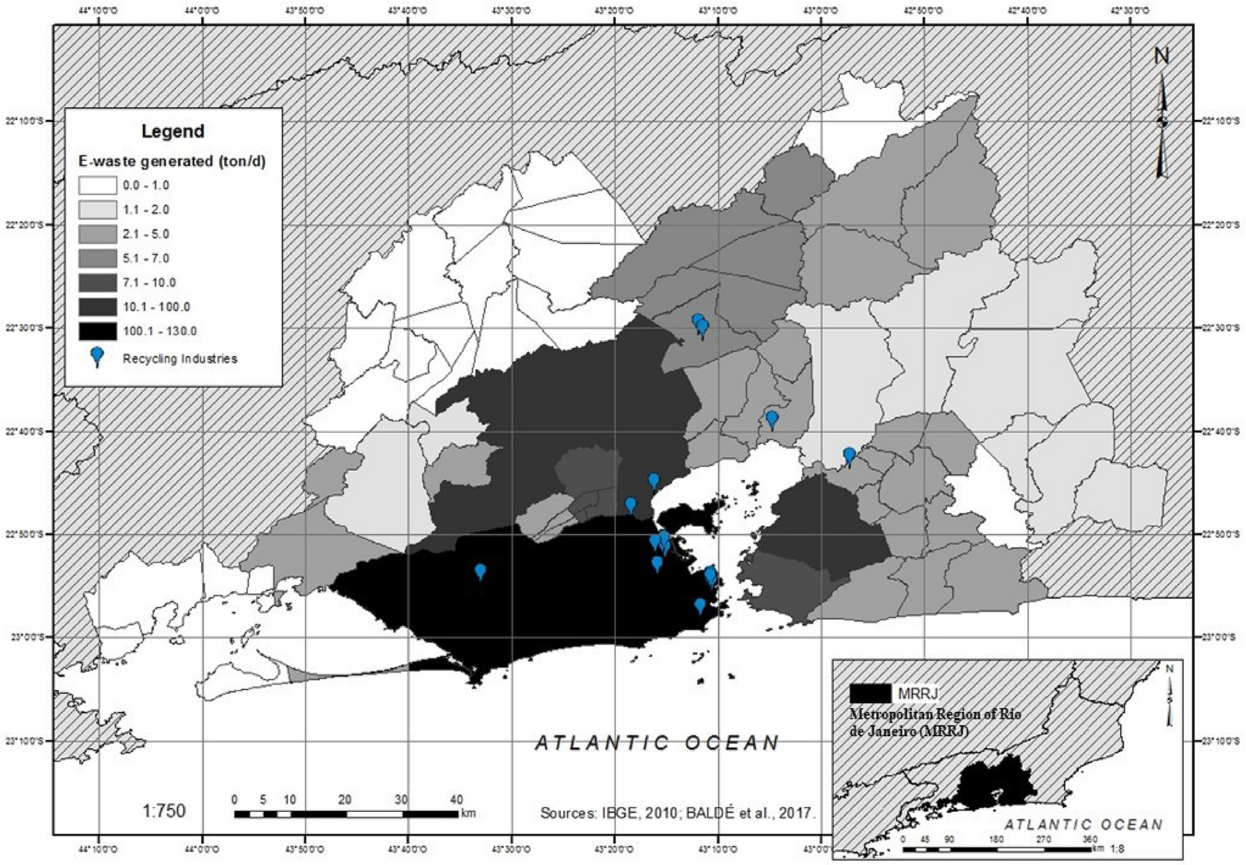

Fig. 5. E-waste recycling industries in the MRRJ and the e-waste generation average in each municipalitySource: Based on IBGE (2010) and BALDÉ et al (2017).

Table 5
Description and dimension of each criteria and indicators for a circular e-waste management.

Criteria	Indicator	Description	Dimension
Distance (hotspots – industries)	Fuel expenses	L fuel spent for the route	Environmental
	Type of fuel	Number of renewable fuel-based trucks	Environmental
	Emissions	Amount of CO_2 emitted on the route (g CO_2)	Environmental
	Collection duration	Hours spent on the route	Economic
Proximity (hotspot - hotspot)	Collection frequency	Number of times the truck collects at each hotspot per week	Economic
	Hotspots served by each collection	Number of hotspots served by each collection	Economic
	Neighborhoods served by each collection	Number of neighborhoods served by each collection	Social
Type of recycling industry	Activity branch	Number of e-waste categories processed by the industry	Economic
	Industry size	Amount of e-waste processed by recycler (ton/month)	Economic
Local context (hotspots)	Existence of municipal solid waste management plan	Existence of municipal solid waste management plan (Yes/no)	Environmental
	Benefited workers	Number of workers involved with this route	Social
	Educational campaigns	Number of annual campaigns to increase participation of local residents with the disposal of their e-waste	Social

distances between both hotspots and industries and between the hotspots themselves the more circular the e-waste management tends to be. The type of the recycling industry is also worth mentioning, since it indicates how many hotspots the company can comply with. The larger and more diversified the company, the greater the chances that the chosen route will be more aligned with the circular economy assumptions, as it can provide more infrastructure to receive higher amounts of e-waste. Furthermore, the local context considers the particularities of the hotspots in terms of specific environmental regulations, and social gains besides educational programs related to the establishment of the routes. The existence of these parameters contributes for and increased flow in the analyzed route.

4.2.2. Routes

The map in Fig. 6 indicates both the main e-waste generation hotspots with a daily generation over 40 kg in a census tract scale, and the current e-waste recycling industries. It is possible to sketch the main routes for e-waste reverse logistics in the MRRJ, considering the 35 hotspots and the 24 e-waste recycling companies identified.

Fig. 6 was divided into five main routes on the map, focusing ona

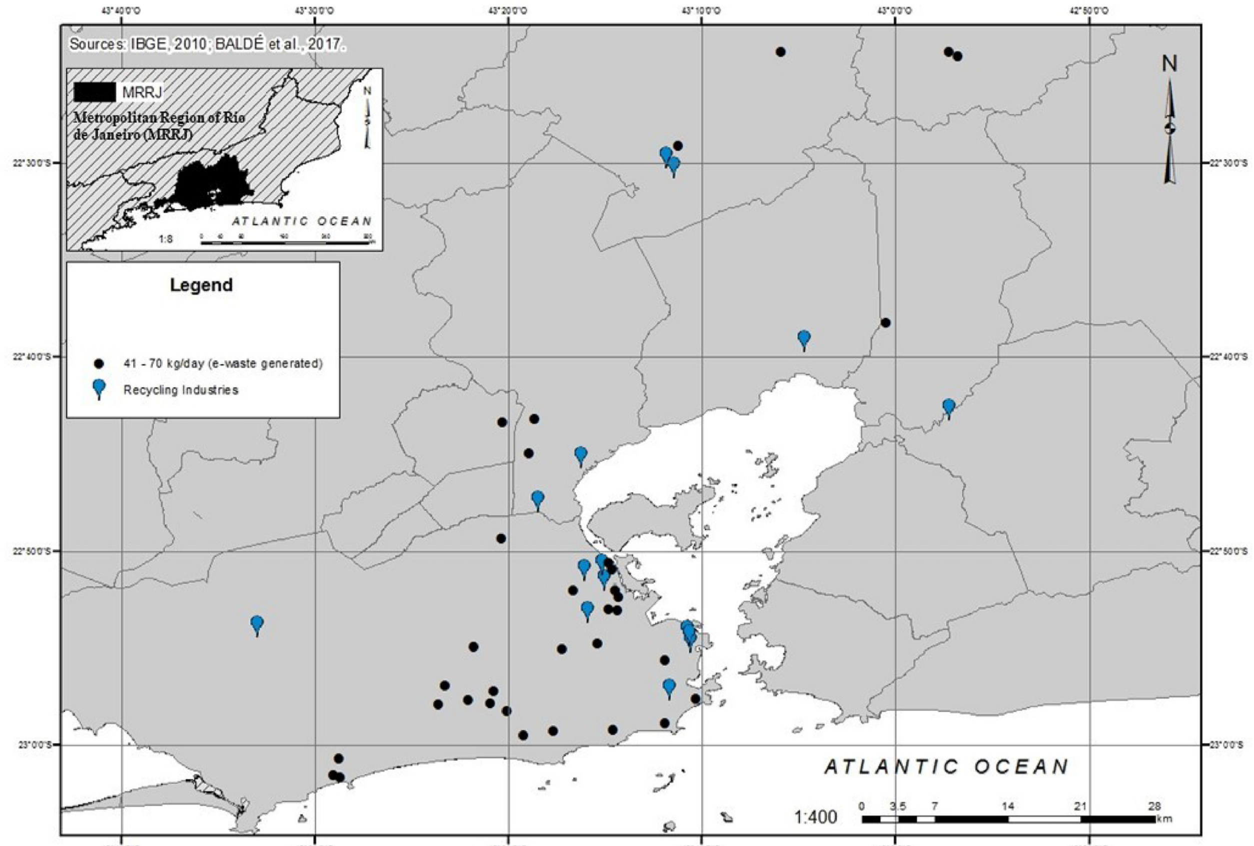

Fig. 6. Main e-waste generation hotspots and the location of the recycling industries in the MRRJ
Source: Based on IBGE (2010) and BALDÉ et al (2017).

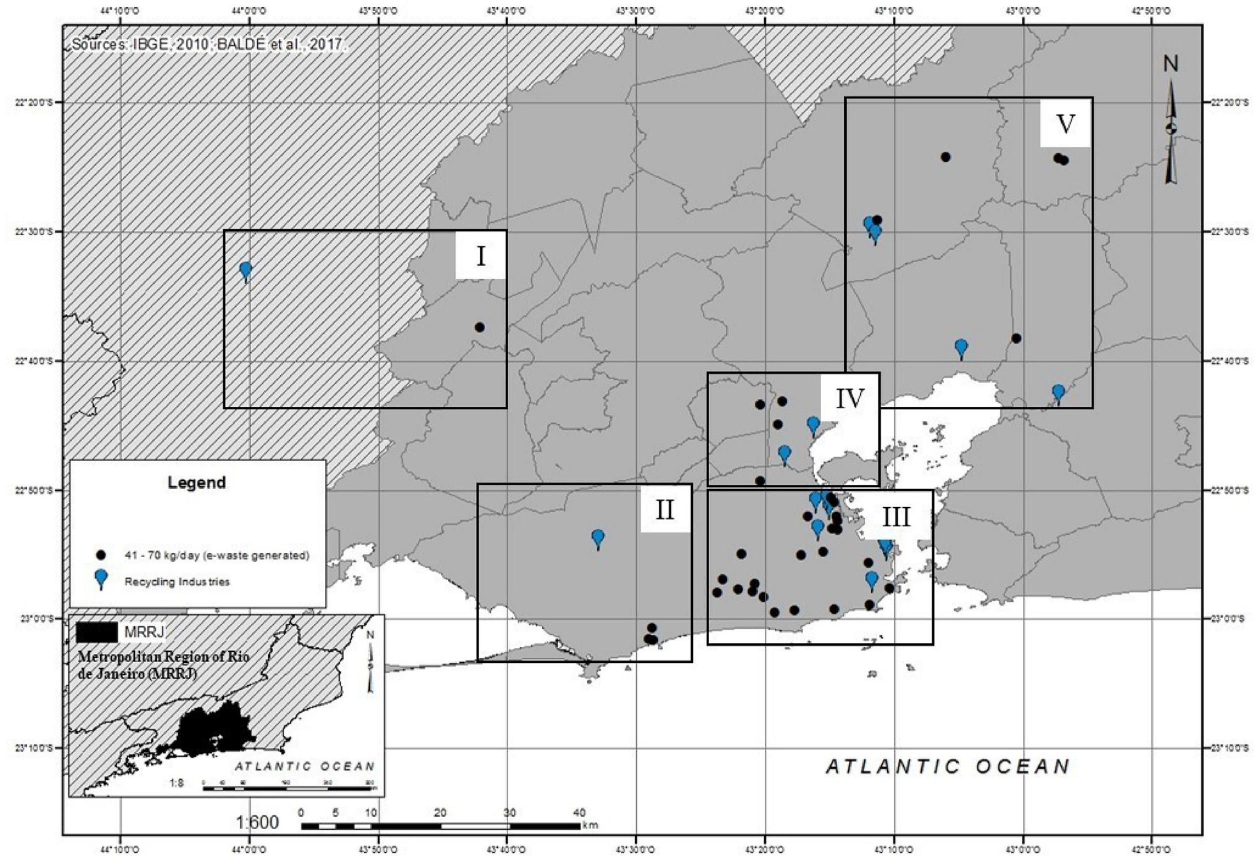

Fig. 7. Main routes for e-waste reverse logistics in the MRRJ
Source: Based on IBGE (2010) and BALDÉ et al (2017).

more detailed analysis from the possible paths going from the hotspots to the recycling industries. Fig. 7 shows the five main routes adopted in this study selected according to the proximity between the company and the hotspots.

The distances between each hotspot and the closest Recycling Industry were measured using ArcGIS measuring tool. The optimum routes were selected considering the shortest distances between the companies and the hotspots, between each hotspot, each recycling company type, and the local context. Table 6 presents the results related to the hotspots, the most adequate Recycling Industry according to the criteria established in Section 4.2.1 and the distances from each one as well.

In Table 6, we can observe that the MRRJ currently has an adequate number of recycling industries in its central part. However, the municipalities at the extremes present a reduced number of such companies, which increases the distances between the hotspots and the industries. In these cases, an alternative option could be the designation of appropriate spaces for temporary e-waste storage. This option would promote segregation and more efficient collection (Palomar et al., 2019) as the collections can be performed in longer time periods compared to the regions with more recycling industries.

4.3. *Limitations of this research*

This study relies on indicators from external sources such as GDP, amount of e-waste generated per inhabitant, amount of VDP required per inhabitants, population, etc. Thus, this study is, by definition, limited by the accuracy of these external indicators. Some may be regarded as highly accurate (e.g. population of a given municipality), but others are too broad to be taken with a high level of confidence (e.g., the figure provided by ABDI (ABDI, 2013) are for the entire country). Moreover, when estimating e-waste generation, this research used sales rate and product lifespan, which, as mentioned previously, do not consider the particularities of this region in terms of social and economic development. Yet another limitation was the identification of the companies. While effort was put to make the search as comprehensive as possible, it is possible that some were missed, which would modify the results of this research to a small extent. Finally, it is noteworthy that this study deals with a specific region of a huge country — Brazil. Therefore, while some of the results can be extrapolated to the rest of the nation, this should be done with care, given Brazil is very diverse in terms of geography, population density, culture, road infra-structure, etc.

5. Conclusion

The current scenario analyzed herein reveals a significant e-waste generation in the MRRJ along with the tendency of distribution of the recycling industries according to the main hotspots. This paper aimed to present the possible fluxes related toe-waste management in the MRRJ, from the generation phase to the treatment processes at different levels and the best possible solutions, giving thought to a set of criteria and indicators proposed. It is important to highlight the influence of exportation rates in future studies since most of the valuable components and materials are currently sent to other countries where there is proper technology to extract the strategic elements for the industry.

Table 6
Routes from the main hotspots of e-waste generation to the closest recycling industry.

Route	E-waste Hotspot	Distance Hotspot - Recycling Industry (km)	Recycling Industry
I	1	53	Ecotronic
II	2	26	Futura
	3	26	Futura
	4	27	Futura
III	5	22	COOPAMA
	6	22	COOPAMA
	7	15	COOPAMA
	8	18	COOPAMA
	9	16	COOPAMA
	10	19	COOPAMA
	11	17	COOPAMA
	12	19	COOPAMA
	13	14	COOPAMA
	14	9	Recicloteca
	15	4.5	Recicloteca
	16	3.5	Recicloteca
	17	4.5	TI-RIO
	18	3	COOPAMA
	19	6	COOPAMA
	20	5.5	COOPAMA
	21	5.5	COOPAMA
	22	2	Zyklus
	23	2	Zyklus
	24	3	Zyklus
	25	1.5	Lorene
	26	2	Lorene
IV	27	14	Prorecicle
	28	7.5	Prorecicle
	29	11	Prorecicle
	30	9	Prorecicle
V	31	12	Fox
	32	4.5	Ecoponto Mosela
	33	23	Ecoponto Mosela
	34	43	Essencis
	35	43	Essencis

Accordingly, as shown in this study, Rio de Janeiro presents great potential for Urban Mining, as an important e-waste generator capable to expand the electronics market with reference to the value extraction from its waste. To invest in proper technology is up to the decision makers, in addition to research and development to increase Rio de Janeiro's autonomy in extracting value from e-waste. Furthermore, the study emphasizes the need to establish a solid and reliable database to ensure management control of the informality in this segment, besides a constant evaluation of better routes for Urban Mining. These facts contribute to the consolidation of new business models, to the enhancement of agents, materials and processes pertinent to the circular economy.

Author contributions section

Marianna Ottoni: Conceptualization, Methodology, Writing - original draft preparation, Writing - reviewing and editing.

Pablo Dias: Writing - original draft preparation, Writing - reviewing and editing.

Lúcia Helena Xavier: Methodology, Writing - original draft preparation, Writing - reviewing and editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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