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Brazil's Formal E-Waste Recycling System: From Disposal to Reverse Manufacturing

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Abstract: This study investigates the post-regulation scenario of waste electrical and electronic equipment (e-waste) reverse logistics in Florianópolis, an island in southern Brazil, following Decree N° 10240/2020. Employing a case study approach, involving observation and semi-structured interviews, the research explores key stakeholders' roles. The results indicate collaborative efforts among the municipal cleaning service provider, recycler, and manager entity, supporting effective e-waste take-back systems. This cooperation not only strengthens the formal recycling market but also yields socio-environmental benefits. The study reveals that optimal outcomes arise from the collaboration between the public cleaning service provider and the business sector, fostering a mutually beneficial relationship. Concerning e-waste value recovery, there is a notable inclination to extend the life cycle of small equipment, emphasizing reuse and remanufacture cycles, while larger electrical and electronic items follow to recycling and recovery cycles. In summary, this research contributes to aligning stakeholders in e-waste reverse logistics, emphasizing compliance with legislation and fostering a deeper understanding of roles, functions, and alliances. The study provides a strategic and structured perspective on e-waste management in a city renowned for selective waste collection and considered a national benchmark for reverse logistics, reinforcing its commitment to sustainability.

Keywords: circular economy; developing countries; e-waste; reverse logistics; waste management policy

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1. Introduction

Disruptive innovation has led to the increased obsolescence and accelerated replacement of electrical and electronic equipment, resulting in the rapid growth of waste electrical and electronic equipment (e-waste) worldwide. However, amidst the challenges in e-waste management, the recovery of secondary raw materials from e-waste presents an attractive business opportunity [1].

Brazil stands as the major e-waste generator in South America, generating approximately 2.1 million tons annually, with an average of 10.2 kg per capita in 2019 [2]. The estimated value of the raw materials in this e-waste stream reaches about USD 57 billion, yet only USD 10 billion are currently recovered in an environmentally sound manner [2]. Surprisingly, the increase in e-waste generation per inhabitant surged by 40% in Brazil between 2016 and 2019 [2,3], while the population growth remained less than 2% [4].

In this context, Brazil enacted Decree No. 10240/2020, establishing the formal reverse logistics system for e-waste [5], in alignment with the Brazilian Policy on Solid Waste (Law No. 12305/2010). This policy emphasizes shared responsibility for the life cycle of products, involving manufacturers, importers, distributors, traders, government, and consumers in waste management [6].

One crucial function of reverse distribution channels is the return of waste (or even post-consumer product) from the consumer to the recycling industry [7]. To optimize the

effectiveness of reverse channels, it is essential to identify and strategically manage them. Thus, this paper aims to map and describe the reverse channels of electrical and electronic equipment in the post-consumption phase, specifically considering the scenario after the regulation of e-waste reverse logistics through the Decree N° 10240/2020. Data were collected through observation and semi-structured interviews and analyzed using the content analysis method. Key stakeholders involved in e-waste reverse logistics were interviewed.

Our investigation focuses on Florianópolis, a city located on an island in southern Brazil, with an approximate population of 500 thousand inhabitants [8]. As an island city, Florianópolis faces unique waste disposal constraints, making it an interesting case study. It was the first Brazilian city to implement selective waste collection [9] and is included in the list of mandatory reverse logistic implementation [5].

To the best of our knowledge, there have been no prior studies characterizing e-waste reverse channels in terms of actors' functions and their interconnections in Florianópolis or similar cities. This research aims to provide valuable insights for strategic decision making by public and private sectors, as well as society. By aligning stakeholders in the implementation of e-waste reverse logistics, this study seeks not only to fulfill legislative requirements but also to foster mutual understanding, value functional contributions, and create collaborative alliances among stakeholders. The results of this study support Florianópolis' vision of becoming the first zero-waste capital in Brazil by 2030, as outlined in the municipal solid waste valorization proposal [10].

2. Methodology

The research strategy was divided into three phases, as presented in Figure 1: (I) literature review, (II) identification of reverse channels of electrical and electronic equipment, and (III) scenario analysis.

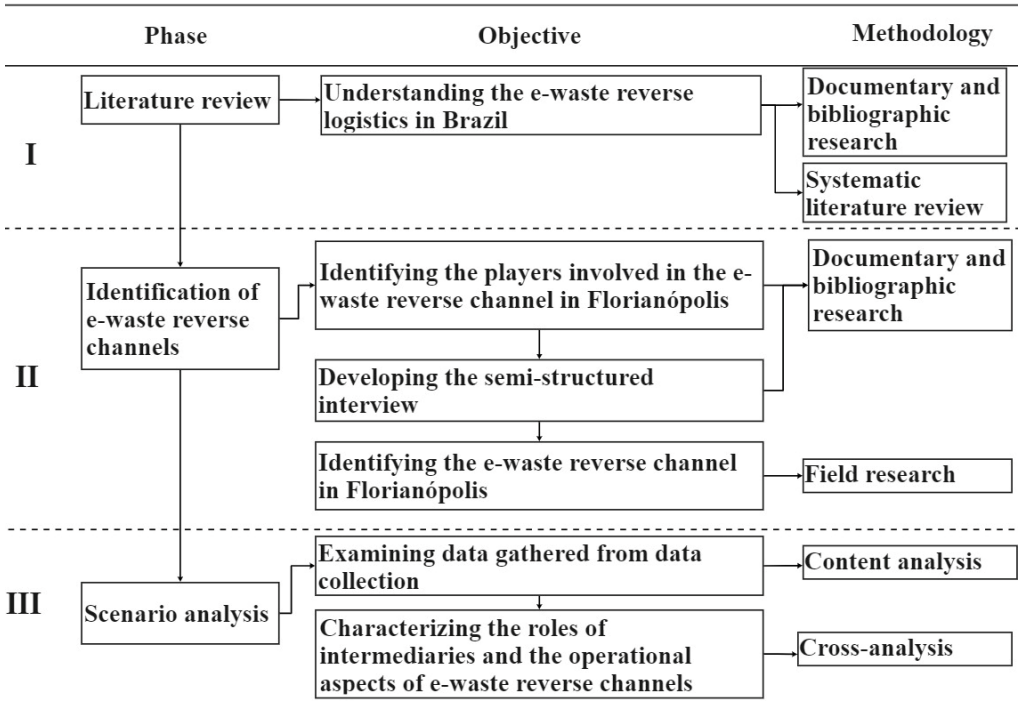

Figure 1. Research strategy.

Based on the data from the field research, we identified the e-waste reverse channel in Florianópolis, in order to understand the pathways that such residue takes at the end of its life cycle, while in the last phase, we examined the data from the interview, identifying the activities related to reverse logistics carried out by the intermediaries of the reverse channels, followed by the characterization of the channels.

Data were collected through observation and semi-structured interviews with key stakeholders involved in e-waste reverse logistics in Florianópolis. Given that the focus of this paper and the geographical scope are quite specific, six key stakeholders (one of them represents two stakeholders; the interviewee from the recycler and logistic operator is also a member of the council of the non-governmental organization) were interviewed, whose details are shown in Table 1. The interviews were performed between December 2021 and February 2022, resulting in approximately 6 h of recording.

Table 1. Description of the actors interviewed.

Company	Stakeholder Description	Contribution to the Research	Interview Length and Date
Municipal Cleaning Service	Senior engineer in the waste collection sector	Contributed to the development and signing of the cooperation agreement for e-waste reverse logistics between the Municipal Cleaning Service and ABREE (manager entity)	45 min interview + 45 min field visit (16 December 2021)
Waste Picker Cooperative	Head of the association	The largest formal waste picker association in the city	50 min interview + 20 min field visit (11 January 2022)
Environmental Educator	Environmental monitor at the city hall	Know-how as an environmental activist, member of environmental education groups, and creates sculptures from e-waste	50 min interview + 20 min field visit (11 January 2022)
Recycler and Logistic Operator	Environmental engineer, founder, and head of the e-waste recycling company	Founder of the largest e-waste reverse logistics company in the Florianópolis region, also contracted by ABREE and approved as a recycler by Green Eletron	53 min interview (3 February 2022) + 60 min field visit (11 February 22)
Non-governmental Organization	Council member of the organization	Member of the organization with the most experience in e-waste reverse logistics	Same interviewee as recycler and logistic operator
State Environmental Agency	Head of the state strategic program for waste management and reverse logistics	Founder of the "Penso, Logo Destino (Literally translation to If I think, then I dispose)" Program, which aims to raise awareness and involve consumer in the proper disposal of solid waste	135 min interview (14 February 22)

The interviews started with two central actors of the e-waste reverse logistics—municipal cleaning service provider and recycler (who also serves as a logistic operator). The manager entities in charge of e-waste are Green Eletron (Manager for Reverse Logistics of Electrical and Electronic Equipment) and ABREE (Brazilian Association for Recycling of Electronic Waste and Appliances). The former manages mainly small equipment, such as laptops and cellphones, with a useful life of 2 to 5 years, composed of metals and plastic, while the latter manages most of the equipment.

Although consumers and informal waste pickers are part of the reverse logistics chain, they were not the focus of this research. The former is because they are not reverse logistics managers, and the latter is due to the difficulty of access, given their informal status. In both cases, a representative sampling of each population would be necessary, which is beyond the scope of this study.

For conducting the interviews, a script was drawn up. The interviews were transcribed with the aid of Transkriptor, an audio-to-text transcription software program, as the interviews were recorded for subsequent content analysis. The analysis of results obtained by interviews was carried out through the categorial content analysis technique as proposed by Bardin [11], the categories were based on the questions from the interview script and their purpose.

According to Souza [12], informal waste management practices are observed in all regions of Brazil, with limited data available for analysis, especially concerning e-waste since its reverse logistics regulation was enacted in 2020. Islam and Huda [13] suggest

qualitative studies, as a way to gain in-depth understanding of practical problems since the majority of publications on reverse logistics and closed-loop supply chain focus on designing and planning reverse distribution. Therefore, conducting the research in the form of a case study aims to contribute to mapping the business context in terms of reverse channel management, without including logistics management in its scope.

The geographical scope of the research is justified by the fact that the city of Florianópolis is included in the list of mandatory reverse logistic implementation [5] and was also the first city to implement selective waste collection in Brazil [9]. There are around 500 thousand inhabitants [8] with a daily generation of domestic waste averaging 1.25 kg per person daily [14]. It is worth noting that Florianópolis is a city where 33% of the workforce is government employees [15], with an average monthly salary of 4.8 minimum wages [8]. These data provide indications of the purchasing power of the residents.

3. Literature Review

3.1. Waste Electrical and Electronic Equipment

There was an increase of 9.2 million tons of e-waste generated globally in 5 years, with 82.6% of the total generated having an unknown destination. While the global average per capita of e-waste generated is 7.3 kg, in Brazil, it is 10.2 kg, making the country the largest e-waste generator in South America [2].

Despite technological advancements having the potential for producing more durable and reverse-logistics-adapted equipment, products are intentionally designed for a short lifespan [16]. The life expectancy of electronic equipment is decreasing, especially small electronic devices such as laptops, tablets, and cellphones [17]. This characteristic also depends on the user's perception of the product and not necessarily on the end of its useful life. Reliable information is lacking, and informality plays a huge role in Brazilian e-waste management [12]. Additionally, collecting primary data at a local, regional, or national scale for decision making in Brazil is challenging [18].

Echegaray [19] states that only 24% of Brazilian consumers attempted to repair their electrical and electronic equipment, with a higher tendency to seek repairs in the case of household appliances. However, most consumers ended up buying a new device due to the lack of a favorable cost–benefit ratio.

Rodrigues, Boscov, and Gunther [20] assert that there are 2.5 electronic and electrical equipment items per household that are stored out-of-use. The same study revealed an acquisition time (length of ownership) of less than 2 years for cellphones, while for most refrigeration equipment, it was over 5 years. In the case of information technology equipment, there is a trend of replacing the devices without them being damaged or faulty due to technological obsolescence (i.e., more fashionable equipment or with new functionalities) [20].

The chosen mode for electrical and electronic disposal depends on the type of equipment [19]. Storing small out-of-use equipment or even disposing of it with household waste was a remarkable behavior [20], while for household appliances, the preference is to sell or donate [19]. Consumers tend to store out-of-use equipment that could be discarded if there was a reverse logistics system operating [20], and 24% of them did not know where to dispose of e-waste. Ghisolfi et al. [21] highlighted that the retention of electrical and electronic equipment minimizes the benefits of the e-waste closed-loop supply chains.

3.2. Reverse Channel

A reverse distribution channel (or reverse marketing channel) for recycling is a bridge between physical and nonphysical gaps that exist between consumers and the recycling industry [7].

Since a reverse channel is established, there is a huge barrier to overcome in the case of altering it as it involves various issues, such as commercial agreements, members involved, documentation, and so forth [22]. Regarding the e-waste reverse channel, there is an even greater need for a systemic approach in defining the channels, as the first actor is the

consumer, who is in control of the responsibility of disposing of e-waste at delivery points but is exceptionally monitored.

Marketing channel power is the ability of one channel member to influence the decision of another member [23]. The power that the "channel captain" (or channel manager) exerts over the other members can occur through coercive power or legitimate power. The former refers to a strict monitoring and punishment approach, while the latter refers to the power of position, expertise, and dissemination of information which results in voluntary cooperation [24].

Souza [12] presents the routes for returning e-waste, from its generation to disposal, demonstrating that the e-waste reverse channels are structured as multichannel systems, with different paths for the waste to move from the consumer to the recycler. The task of coordinating multiple channels forces managers to deal with a variety of challenging issues, especially regarding synergies across channels and building strategic alliances [25]. Therefore, the channel strategy concerns the entire process undertaken by the waste, from the channel configuration, commercial operation, and contracts, and the responsibilities of the members [25].

The marketing channel is considered an interorganizational network consisting of interdependent firms with self-interest goals and a division of tasks and functions [26]. Therefore, it is assumed that negotiations among the involved parties are necessary to achieve the goals of the reverse channel. Governance constructed by local actors could be a thoughtful way to promote e-waste recycling [27].

3.3. E-Waste Flow in Brazil

There are more informal management practices for e-waste in Brazil than formal ones [28]. Informal waste management practices are observed in all regions of the country, with limited data available for analysis, especially for e-waste [12].

The way in which the consumer discards the residue defines the e-waste stream. In formal reverse channels, there is usually adequate treatment and value recovery of materials. On the other hand, in informal reverse channels, the activities of intermediaries are often not routine or lack structure to ensure proper implementation of the recycling activities, which can contribute to an increase in negative impacts on the environment and the health of workers handling such waste [12].

Collecting e-waste through periodic campaigns has been yielding significant results in the municipalities where they are carried out. ABDI [29] suggests this model for small towns that do not have fixed delivery points. Alves et al. [30] state that participation in collection campaigns tends to increase when they are well advertised (through radio, posters, and social media networks) and well structured. The authors observed that the public attending the campaigns was unsure of what materials they could deliver, despite the organizers considering that they had succeeded in awareness campaigns. Many consumers return to the collection site a second time with more waste after seeing the variety of products being delivered by other participants [30].

The fixed collection points model was established by Decree No. 10240/2020, which defines the municipalities with a population of over 80 thousand inhabitants that must implement the reverse logistics system for e-waste by installing at least one collection point for every 25 thousand inhabitants [5]. Although Ottoni et al. [16] suggest combining collection campaigns and fixed collection points in larger municipalities to ensure more visibility and reach the audience, the disposal of large household appliances (e.g., refrigerator, freezer, stove, etc.) is hindered by their size and weight. Collecting through collection campaigns and fixed collection points is more suitable, especially when the distances between the collection points are significant, thereby contributing to environmental education and increasing e-waste collection rates.

3.4. Environmental Regulations for E-Waste in Brazil

The Brazilian law establishes the principle of shared responsibility for waste management, which involves manufacturers, importers, distributors, retailers, consumers, and government entities working collaboratively, with individual responsibilities in each link of the reverse logistics process [6]. Table 2 shows the stakeholder's responsibility, according to Decree No. 10240/2020.

Table 2. Reverse logistics players' responsibility. Source: Based on Brazil [5].

Reverse Channel Member	Responsibilities According to Regulation
Consumer	Dispose of e-waste at the delivery points
Manufacturer and importer	Provide appropriate disposal; collaborate with environmental education and the communication plan; finance the reverse logistics system
Distributor and retailer	Provide consolidation and collection points; inform consumers of their responsibilities (only retailers); collaborate with environmental education and the communication plan
Performance follow-up group	Monitor, support, and supervise the reverse logistics system
Manager entities (ABREE and Green Eletron)	Perform reverse logistics actions, being able to hire or subcontract third parties to provide services
Waste picker cooperatives, public cleaning services, big generators, and non-governmental and related organizations	They can join the reverse logistics system through a contract with companies or a manager entity

Differing from other countries, where producers are responsible for e-waste management (extended producer responsibility), the Brazilian model is complex and brings difficulties in defining the roles and operational responsibilities of each stakeholder, mainly because there are costs involved and attributed to them. While in the countries (mostly in Europe) where the policy is based on extended producer responsibility, the financial, physical, and legal responsibility falls on the producer [20].

After the implementation of Decree No. 10240/2020, the goal is to properly collect and dispose of 17% by weight of the household electronic products sold in the base year 2018, with the installation of approximately 5060 collection points by 2025, covering all Brazilian municipalities with more than 80 thousand inhabitants (400 cities). At the end of the five-year expansion, the reverse logistics system will serve 61% of the country's population [5].

4. Results and Discussion

In this section, we present the results and discussions based on three key aspects of the e-waste reverse logistics system in Florianópolis: collaboration among stakeholders, organizational setup, and operational aspects.

4.1. Collaboration among Stakeholders of E-Waste Reverse Channels

Figure 2 illustrates the sequential indications of the interviewees, considering the inspiration from the snowball sampling method [31], in order to identify the interrelationships among the stakeholders involved in the post-consumer e-waste reverse logistics channels in Florianópolis.

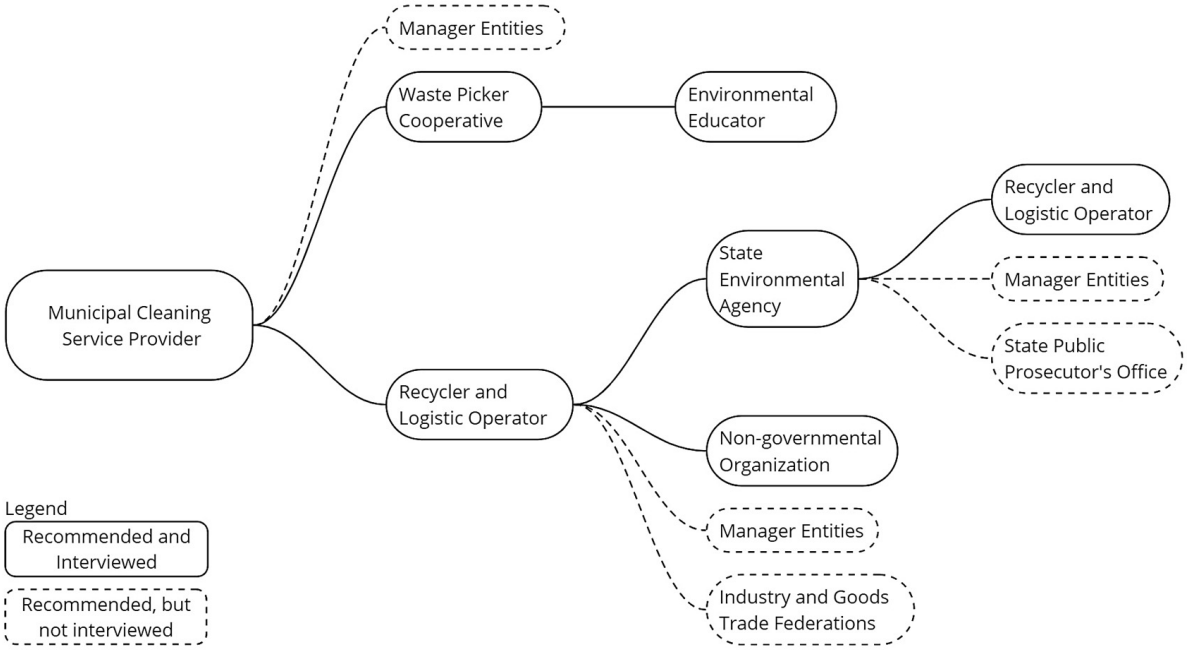

Figure 2. Indication of interviewees through snowball sampling.

The manager entities were mentioned by three out of five interviewees, as presented in Figure 2, with a particular emphasis on ABREE, a manager entity that primarily deals with large household appliances. This result is presumed to be related to the challenges faced by organizations in managing these types of e-waste, which have reverse logistics hindered by their size and weight [16].

The distributing channel cannot function without sustained cooperation among channel members, and the partnership approach fosters channel performance [26]. Legitimate power results in voluntary cooperation, since power is strongly related to trust [24]. The establishment of trust among channel members was observed in the relationship between the recycler and logistic operator and the municipal cleaning service provider, as well as the recycler and logistic operator and the state environmental agency. The trust relationship was evident in the text excerpts and in the viewpoints expressed by the interviewees regarding the recycler and logistic operator. Therefore, it can be asserted that the recycler and logistic operator acts as technical support for decisions that affect the e-waste reverse logistics, as the interviewees reported consulting him in specific cases where he has technical knowledge.

As stated by Vargas et al. [32], ABREE did not disclose on its institutional page the amount of collected e-waste, and the assumption of not having met the targets was confirmed with the publication of the monitoring report by the Ministry of Environment [33]. The reverse logistics performance monitoring reports indicate that ABREE achieved only 11.4% of the required e-waste collection target set by Decree No. 10240/2020 (target 10,924 t; collected 1245 t), while Green Eletron achieved 123% of the target (target 581.83 t; collected 715.83 t) in 2021 [33,34].

Despite the Ministry of Environment informing that the e-waste reverse logistics monitoring report would be delivered by March 2022, there was no response after a new attempt to contact them following the deadline, and furthermore, the reports were published in December 2022. Thus, the need for interorganizational management is reinforced, and forming alliances among the players can foster a collaborative team climate [26], especially in reverse channels structured as multichannel systems [25].

Cooperative relationships were identified between the recycler and logistic operator and the municipal cleaning service provider, as well as the recycler and logistic operator and the state environmental agency. The recycler and logistic operator acts as a facilitator in these relationships, playing the role of an intermediary among stakeholders, including

the manager entities. This configuration helps the resolution of issues and contributes to the advancement of e-waste management in Florianópolis, thereby contributing to the establishment of governance [27].

The "channel captain" has a leadership role [23], especially in e-waste management, where it relies on legitimate power to foster voluntary cooperation [24]. Data analysis reveals that this role is predominantly assumed by the recycler and logistic operator, but also by a certain sector within the City Hall sectors (responsible for environmental matters). These findings align with the conclusion of Giglio et al. [27], which highlights the prevalence of formal governance, with a central logistics management actor seeking to resolve and facilitate action within this formal governance framework.

This can be explained by the fact that the recycler and logistic operator interviewee's role goes beyond technical expertise, stemming from positive relationships with other stakeholders, both at the municipal and state levels, as well as with manager entities. Moreover, his comprehensive understanding of the e-waste reverse logistics context is enriched by intrinsic business experiences. In the case of the City Hall, it interacts with all channel members, including consumers, playing a crucial role in the effectiveness of the reverse channels.

Most of the interviewed stakeholders aligned regarding the role of the City Hall as a facilitator and coordinator of the e-waste reverse channels. Although the mentioned sectors vary, they all fall under the organizational chart of the Municipal Department of Environment. However, the recycler and logistic operator interviewee emphasized that the logistic operators themselves, along with representatives from the business sector (industry and goods trade federations), have the capacity to coordinate the channel.

As the Brazilian Policy on Solid Waste establishes the responsibility of the business sector (manufacturer, importer, distributor, and retailer) for the structuring and implementation of reverse logistics systems [6], the coordination of the reverse channels by the business sector members themselves is considered compliance with the legislation. However, it is worth noting that the obligation of the business sector is limited to a proportion of the electronic and electrical products placed on the market, with the collection and environmentally appropriate disposal targets being below 20% by weight of the household electronic products sold in the base year 2018. Even at the end of the reverse logistic system implementation schedule [6], more than 80% of e-waste can still become municipal solid waste if discarded in the municipal collection (and therefore financed by the citizens themselves, not by the business sector).

To classify the waste, two criteria can be adopted: the origin or the product criteria [35]. The municipal cleaning service provider is responsible for municipal waste management (when it is domestic waste), and the business sector is responsible for products included in the reverse logistics system (product criteria) [35].

On the one hand, Caiado et al. [36] suggest the reverse logistics credit market as a way to endorse the environmental commitment to environmentally sound management and disposal of e-waste. This approach could potentially encourage the business sector to exceed the target proposed by the Decree No. 10240/2020. On the other hand, they highlighted the fact that there is still no regulation for this market. Rodrigues et al. [20] emphasize that the Brazilian e-waste management model is complex, not only in terms of the shared responsibility principle but also due to the dependence on consumer behavior. Therefore, there are indications that the most effective scenario arises when the public cleaning service provider and the business sector collaborate, establishing a mutually beneficial relationship [27].

4.2. Organizational Setup of E-Waste Reverse Logistics

The formal structuring of e-waste reverse channels began through a partnership between the recycler and logistic operator and the municipal cleaning service provider, where the recycler and logistic operator collected the e-waste and subsequently submitted reports to the environmental authorities. Nonetheless, the municipal cleaning service

provider still faced the challenge of providing environmentally appropriate disposal for household appliances, which, for the most part, ended up in scrap yards.

By July 2021, the manager entity ABREE and the recycler and logistic operator formalized a commercial contract, and the municipal cleaning service provider and ABREE established an agreement, reducing intermediaries and formalizing the responsibilities of each involved party in the provision of e-waste management services. In this new scenario, there was an improvement in e-waste management, as illustrated in Figure 3.

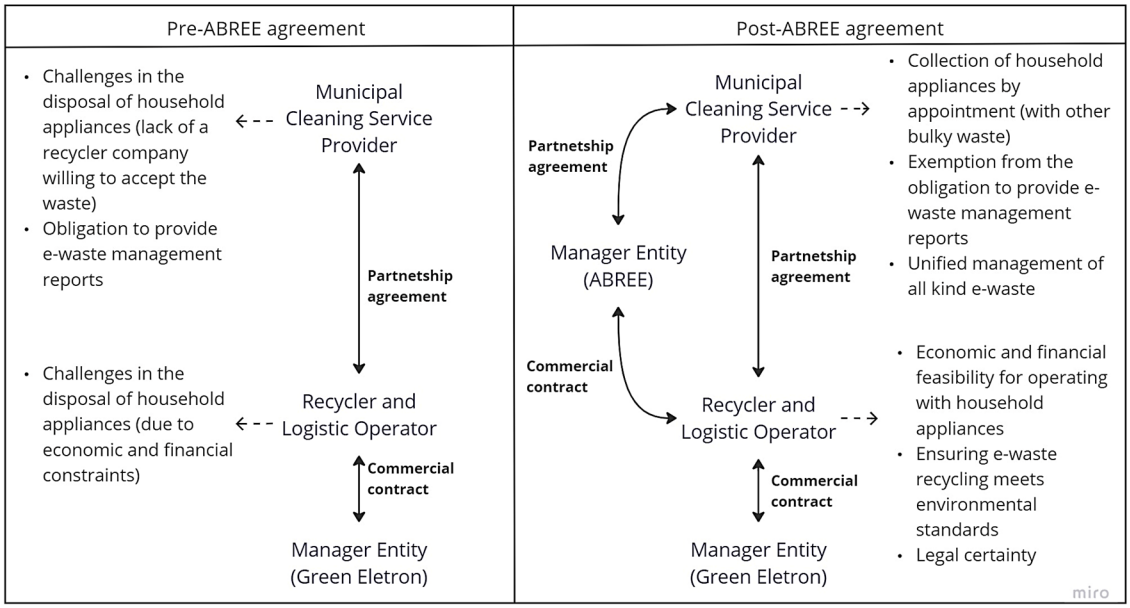

Figure 3. E-waste management changes due to ABREE partnership.

The partnership between the municipal cleaning service provider and manager entity ABREE brought improvements in e-waste management, particularly by integrating the reverse logistics of large household appliances with the usual reverse logistics. Currently, all types of e-waste, regardless of their size, are managed within the same reverse manufacturing line. The implementation of a scheduled bulky waste collection service has reduced the challenges in reverse logistics of large household appliances, as pointed out by Ottoni et al. [16]. Moreover, this partnership fosters a greater tendency for e-waste to follow a flow that converts them into secondary raw materials, given the improved reverse logistics infrastructure and the consolidation of the network of partner recyclers. In addition, e-waste is challenging to dispose of, and hence, efforts are also made to facilitate the disposal of these residues [28].

Reverse logistics should be financed by the business sector [5]. However, if e-waste is improperly disposed of through municipal waste collection or in public areas, the cost of management will fall on society, as urban solid waste management is funded through municipal fees (e.g., property tax (the Brazilian property tax is known as Urban Building and Land Tax, and it is paid every year, by the owner (or the tenant) of the house, building, or land plot)). Additionally, the value embedded in the purchase of products intended for reverse logistics is not passed on by the manager entity to municipalities, a situation strongly influenced by the concept of shared responsibility, as defined in the Brazilian Policy on Solid Waste [6].

One of the main differences from the European Union's policy lies in the concept of extended producer responsibility, which demands that manufacturers take financial, physical, and legal responsibility for waste management, unlike Brazil, where responsibility is shared. In practice, the shared responsibility concept has led to various discussions when defining waste policies, as exemplified by the agreement regarding electrical and electronic equipment, whose discussion began in 2011 and was only concluded in 2019.

According to the agreement established between the manager entity ABREE and the municipal cleaning service provider, there is no provision for monetary transfers from the manager entity to the municipality. On the other hand, in the commercial agreement between ABREE and the recycler and logistic operator, there is remuneration for the recycler, even though the municipality handles transportation and primary storage. Thus, if there is proper discarding performed by the consumer, costs for the municipality can be reduced—which, in turn, depends on the effective participation of the consumers in the reverse logistics system.

4.3. Operational Aspects of E-Waste Reverse Channels

Figures 4 and 5 illustrate the stakeholders involved and the flow of e-waste return from consumers to recyclers.

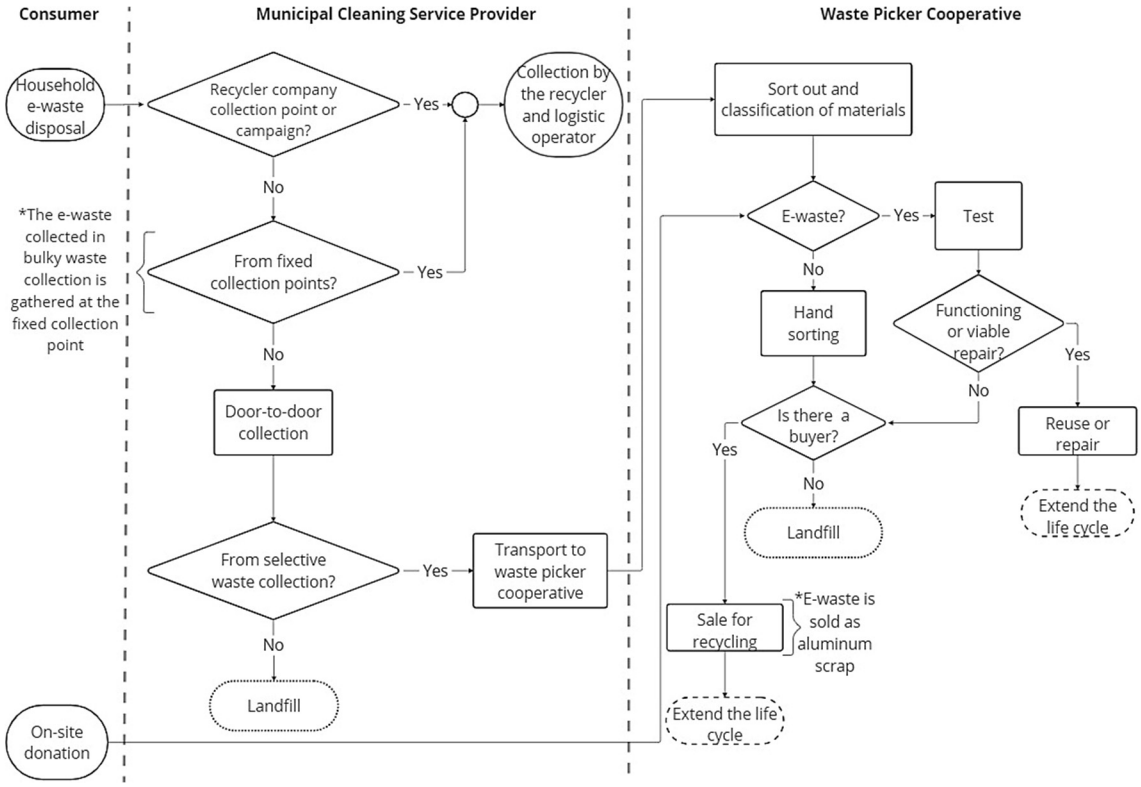

Figure 4. Reverse channels of electrical and electronic equipment in Florianópolis (from disposal to collection). * Additional information.

While electronic and electrical equipment is in the consumption phase, consumers are responsible for extending the product's lifespan through strategies like refuse, reduce, reuse/resell, and repair. In the reverse logistics phase, the treatment of the electrical and electronic equipment begins [16]. As observed in Figure 4, the way the electrical and electronic equipment is discarded by the consumer will define its flow, as also suggested by Souza [12]. Thus, there is the possibility of either the final disposal of e-waste in a landfill or its inclusion in a valorization stream, extending the life cycle.

Once the consumer discards e-waste at the appropriate locations (i.e., collection points), they are directed toward the reverse logistics system. This process ensures a proper destination will be given, either through reintegrating the materials as secondary raw materials into recycling processes or into the second-hand market. However, having a well-structured reverse logistics system is not enough, and consumer participation is essential [32]. Although Florianópolis provides various reverse channels (door-to-door collection of bulky waste, collection points operated by the recycling company, and collection points managed by the public cleaning service provider), it is still evident that e-waste is being discarded

mixed with other types of waste, in vacant lots, and very likely in landfills, reinforcing findings from previous studies [12,37].

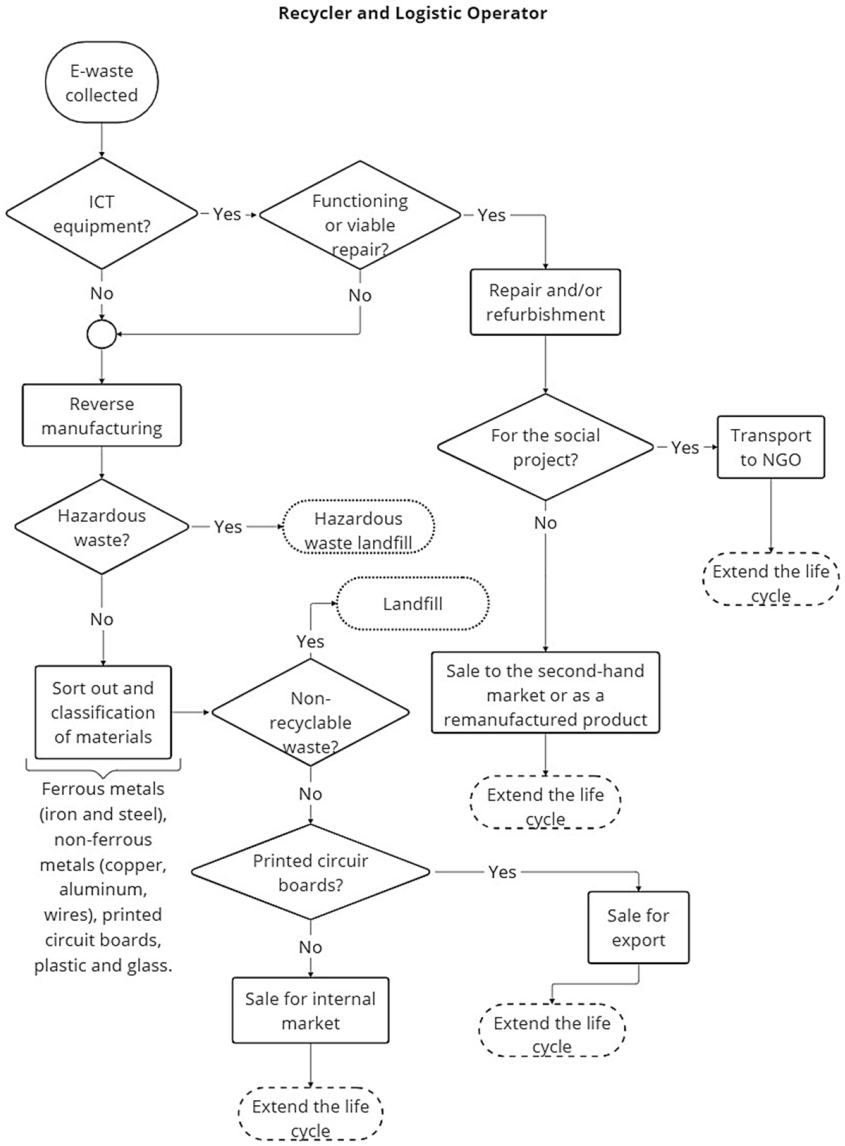

Figure 5. Reverse channels of electrical and electronic equipment in Florianópolis (from collection to reverse manufacturing).

The sorting out and classification of materials are based on the types of materials (see Figure 5): ferrous metals (iron and steel), non-ferrous metals (copper, aluminum, wires), printed circuit boards, plastics, glass, and hazardous waste. The recycler and logistic operator explained that the market is no longer favorable for the company to act as an exporter of printed circuit boards. Therefore, all the material is sold within the country to companies in São Paulo, which have representatives in Santa Catarina. As for the printed circuit boards, the sale is directed to a representative company of the refinery itself in Brazil, which exports the material. On the other hand, the other materials are recycled in Brazil; De Oliveira Neto [1] reported similar findings.

In the case of e-waste mixed with household waste, the reverse path includes at least one additional actor, which is the waste picker cooperative (see Figure 4), as the recyclable waste collected by the municipality is donated to these associations. In the interview with a waste picker cooperative, we are informed that small electronic waste is usually mixed with recyclables.

During the field visit at the waste picker cooperative, parts of larger household equipment, such as washing machine parts, were observed in the external area of the sorting warehouse. The waste picker cooperative interviewed stated that, in the past, they used to sell the e-waste to different companies after sorting. However, since the buyers did not provide an invoice, they started selling it as aluminum scrap to only one buyer in the Florianópolis metropolitan region. Despite paying lower amounts, this buyer provides an invoice.

In the context of e-waste recovery, Table 3 shows the collection of e-waste in Florianópolis by the municipal cleaning service provider, including e-waste from fixed collection points and scheduled large household appliance collection. The regulation of e-waste reverse logistics (enacted in 2020) increased e-waste collection. According to the municipal cleaning service provider, the most significant volume comes from deliveries at fixed collection points.

Table 3. Amount of e-waste collected by the municipal cleaning service provider. Source: Based on PMF [38].

Year	2017	2018	2019	2020	2021	2022	2023
Amount collected (t)	32	24	22.5	46	67	55.3	102.1 *

* Data collected in October 2023.

It is worth noting the legal support that waste picker cooperatives have in disposing of the materials that are not suitable for recycling to the landfill. In other words, the materials processed by the cooperatives for which there are no buyers become waste and, therefore, have the landfill as their destination—even though they could be recycled by other companies that have a consolidated network of partners for each material, as is the case of the recycler and logistic operator.

Moreover, as reported by the interviewee from the recycler and logistic operator, waste picker cooperatives are among their main competitors. Ghisolfi et al. [21] emphasize the lack of bargaining power of waste picker cooperatives as a critical factor for their inclusion in formal e-waste management, such as in terms of the volume of materials collected for commercialization (economies of scale) and the physical infrastructure of their warehouses.

Additionally, waste picker cooperatives are allowed to be part of the formal reverse logistics system if they are legally established and qualified [5], which is not the case in Florianópolis. Therefore, when e-waste deviates from the most appropriate reverse channel, the chance of it becoming secondary raw material decreases. Recyclable material will only become secondary raw material if there is a buyer for it, so even though a material may be considered recyclable by the recycler, it may not be recyclable for the cooperative due to the absence of a purchaser.

Figure 5 also shows that the recycler and logistic operator performs e-waste valorization processes, most of them for recycling purposes, while in the case of information technology, equipment for repair and reconditioning. These processes are decentralized, requiring a network of partner recycling companies [1]. The recycler and logistic operator collect the e-waste from the municipal cleaning service provider, whose annual quantity is specified in Table 3. They disassemble, sort out, and classify the materials, subsequently selling them to recycling companies, which carry out physicochemical processes. Quantitative data for material flow analysis post-collection by the recycler and logistics operator were not attainable.

De Oliveira Neto et al. [1] found that the e-waste reverse logistics market is promising both in economic and environmental terms. Vargas et al. [32] discussed the advances in implementing e-waste reverse logistics after the regulation through Decree No. 10240/2020, as it brought both market opportunities and legal certainty for the stakeholders involved, which is also corroborated by this paper in the Florianópolis scenario.

In identifying the roles and limitations of the stakeholders in the e-waste reverse logistics, we can highlight some points. The State Environmental Agency expressed that

one of its main tasks, as a regulatory body, would be to verify the Solid Waste Management Plans, which is a requirement within licensed activities. However, it has been a strategic partner to municipalities with the "Penso, Logo Destino" Program, as a mediator between the city hall and the manager entities in the reverse logistics process. The program aims to support proper solid waste management, involving stakeholders and raising awareness about this issue among them.

In summary, there are defined roles for each of the actors, typically through formal documents (agreements or contracts). Meanwhile, regarding the regulation of the reverse logistics system, the system is self-regulated, meaning that e-waste reverse logistics was already being implemented prior to the regulations, even without clear roles for the stakeholders.

Finally, improvements in the e-waste reverse logistics infrastructure and also in the cooperation among the stakeholders were observed. The interviewees emphasized that Florianópolis is considered a national reference in terms of reverse logistics. The formalization of relationships among the involved parties through contracts and agreements has enabled them to move away from the gray area where responsibilities were unclear. Although there are challenges in obtaining primary data [18] to estimate the progress in the e-waste reverse logistics, we understand that, despite not being in an ideal condition, the municipality is continuously improving its solid waste management.

5. Perspectives

Under the influence of e-waste reverse logistics regulation, there has been a boost in actions toward the implementation of e-waste reverse logistics, aiming to align with the legislation and promote the transition to a circular economy. However, from a macro-perspective, the transition to a circular economy model is not seen yet.

In the context of e-waste valorization, there is a greater tendency to extend the lifespan of information technology equipment when they are in the post-consumer condition or as components (i.e., parts or pieces), emphasizing reuse and remanufacture processes. Meanwhile, the majority of e-waste proceeds to material cycles (i.e., sorted out as iron, plastic, etc.) and substance cycles (i.e., chemical components), contributing to recycling and recovery processes.

Although the Brazilian Policy on Solid Waste is a federal law, each state has its own peculiarities, making it unfeasible to compare the scenario in Santa Catarina with other states in the North and Northeast regions, where most of the waste from these regions is still disposed of in controlled landfills or open dumps.

Therefore, we suggest proposing state-specific targets that are suitable for the respective scenarios instead of national targets, as outlined in Decree No. 10240/2020, which do not consider geographic issues and waste management maturity. Besides that, the regulation allows for the proposition of state-level agreements that define more demanding targets than those established by the federal government. We are of the opinion that the capacity for the collection and disposal of e-waste in regions that have maturity in waste management, meaning they are more advanced in terms of compliance with environmental regulations (such as waste collection and disposal infrastructure, recycling industry, and other infrastructure characteristics), as is the case in the South and Southeast regions, exceeds the requirements set by the regulation.

Moreover, a well-structured e-waste reverse logistics system is not sufficient if there is no consumer participation, as the way consumers dispose of their waste determines the flow it takes. Therefore, we suggest aligning efforts in environmental education, particularly focusing on selective collection, as well as increasing the fixed collection points around the city. According to this research, as awareness initiatives and the availability of collection points increased, the collection of this type of waste also increased. There is an indication of progress in the e-waste scenario in the municipality, including prospects for improvements, as the stakeholders in the e-waste reverse channels are linking strategic actions. Thus, there

are indications that the most effective scenario arises when the public cleaning service provider and the business sector collaborate, establishing a mutually beneficial relationship.

It is interesting to note that as the relationships between the municipal cleaning service provider, the manager entity, and the recycler and logistic operator became consolidated, there was a significant improvement in the e-waste reverse logistics, especially for larger household appliances due to bulky waste collection by the municipal cleaning service provider. The legal certainty not only brought stability to the management of the reverse logistics system but also resulted in socio-environmental benefits.

6. Conclusions

This paper contributes to aligning the stakeholders in the implementation of the reverse logistics for e-waste, aiming not only to meet the legislation requirements but also to help them understand their role, value their functions, and create alliances with other stakeholders. Our research introduces a strategic and structured perspective on the management of e-waste in a city that is the pioneer in selective waste collection and a national reference in terms of reverse logistics. Therefore, it supports strategic decision making by both the public and private sectors, using the model adopted in Florianópolis as a framework for other cities.

Additionally, we should mention the limitations of this research. Not all possibilities of contacting interviewees, both formal intermediaries of the e-waste reverse logistics and regulatory bodies, were exhausted. Informal players of reverse logistics, such as individual waste pickers, electronics repair services, and consumers, were not included in the scope of this work.

Acknowledging the research's limitations, with some avenues of contacting formal intermediaries and regulatory bodies unexplored, we recognize the absence of informal players like waste pickers, repair services, and consumers in our scope.

As a qualitative study, generalizations are limited, considering the unique scenarios of each municipality in terms of political management, the level of Brazilian Policy on Solid Waste implementation, and the overall functionality of e-waste reverse channels.

Further studies may focus on analyzing the feasibility of the implementation of more demanding e-waste reverse logistics, with more ambitious targets than the one required at the national level. Finally, applying this research in cities that are comparable to this case study would provide valuable contributions to the field of e-waste reverse logistics.

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