Systematic literature review on reverse logistics of waste electrical and electronic equipment: recommendations and opportunities for future research

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Abstract. The exponential consumption of Electrical and Electronic Equipment (EEE), together with the absence of Reverse Logistics process (RL) and sustainable production, contribute to the generation of Waste Electrical and Electronic Equipment (WEEE) in significant quantities. For these reasons, the number of researches on the subject increases annually, mainly in countries that have a higher rate of WEEE generation. The need to implement an RL system within regulatory conditions and appropriate techniques has become a challenge. Thus, the objective of this systematic literature review is to better understand the current state of WEEE reverse logistics, and thereby identify the gaps, in order to outline future directions for research on the topic. The results showed that the Asian continent had a greater number of countries with research and publications on the subject. Most studies applied the following research methods: case study, and modeling and simulation. Among the 48 articles analyzed in detail, none proposed the application of the agent-based simulation method. A good way to start research on the topic is by using keywords such as: Reverse Logistics, E-waste, Electronic Waste, WEEE and Sustainability.

Keywords: Reverse Logistics, E-waste, Systematic Literature Review.

1 Introduction

According to the Global E-Waste Monitor 2020 report by the United Nations (UN), the amount of Waste Electrical and Electronic Equipment (WEEE) reached the unprecedented mark of 53.6 million tons of waste generated worldwide, just in 2019, and unfortunately, only 17.40% of this amount was recycled [1]. The United Nations Institute for Training and Research [2] warns that the amount of e-waste generated will double by 2050.

The exponential growth in the generation of WEEE is a consequence of the increase in sales, of the manufacturing speed and of the speed with which Electrical and Electronic Equipment is replaced by the population [3]. The income level, the policies

in force and the structure of the waste management system are also factors that interfere with the disposal behavior [1].
With the purpose of mitigating the harmful effects to the environment and the population, as well as providing economic gains, reverse logistics (RL) is the alternative to attenuate the problems approached [4].

To put the sustainable reverse logistics system into practice, it is necessary to integrate different stakeholders, in order to overcome existing barriers, such as lack of awareness, absence of data and technical knowledge in WEEE management, as well as the existence of an illegal recycling market [5] [6].

The need to institute a reverse logistics system in accordance with appropriate regulations and techniques has become a huge challenge. With this, it attracted the attention of scientific, entrepreneurial, non-governmental and governmental organizations around the world [7]. In view of this, the objective of the present study is to better understand the current state of the reverse logistics of WEEEs. Based on this objective, this study aims to answer the following questions:

- Question 1: How is the publication of articles on WEEE reverse logistics progressing?
- Question 2: Which countries do more research on the topic?
- Question 3: What are the main areas of interest in WEEE reverse logistics?
- Question 4: What are the keywords used to start a search about RL?
- Question 5: What are the research methodologies used?
- Question 6: What are the most searched types of e-waste?
- Question 7: What are the main issues/topics approached in the reverse logistics of e-waste by the academic community?
- Question 8: What are the existing gaps?

Through the answers to the research questions, this article will provide an overview of the studies carried out on WEEE reverse logistics. In addition, it will provide information to other researchers to start studies on the subject from the identification of gaps.

2 Research Methodology

The present study is a systematic literature review (SLR) with the objective of mapping the state of the art of the LR of WEEEs. The SLR is a methodology in which published articles are selected, with the purpose of analyzing, evaluating, synthesizing, reporting data and evidence, in order to allow conclusions about what is and what is not known [8]. For the development of this research, the 5 steps proposed by [8] were used.

In the step 1 was realized and the following research question was formulated: what is the current status of research carried out in the area of reverse logistics of Waste Electrical and Electronic Equipment? From this main question, 8 secondary questions, presented in the first section of this study, were elaborated.

To carry out step 2, the database consulted was Scopus, because it is considered one of the most relevant sources of peer-reviewed studies [9]. The keywords used in the

search were “reverse logistics”, because of its generic and comprehensive character, and “electronic waste”, to better delimit the theme. Quotation marks and the Boolean operator “and” were used in the keywords. The search resulted in a total sample of 145 publications between the years 2007 and 2022, making it possible to realize the first analyzes and answer the questions 1, 2, 3 and 4.

Out of the 145 publications, only the articles in English with open access were chosen. With that, the 39 most cited and the 63 most current articles were selected, totaling 102 articles.

For step 3, exclusion criteria were analyzed, such as studies that approach other types of waste, for example, urban waste, batteries, photovoltaic and tires, articles that were duplicated, that is, that were present both in the most cited and in the most recent articles. After analyzing the 102 articles, it was found that 14 articles were about other types of waste, 17 articles didn’t have open access and 23 were duplicates. Thus, the total number of articles was 27 most cited and the 21 most current articles. Based on this analysis, it was possible to answer the remaining questions (5, 6 and 7).

The articles were registered using the Mendeley Reference Manager software. In addition, Microsoft Excel software was used in order to develop the classification structure of articles and analyses. For step 4, graphs were constructed, in order to synthesize and integrate information and results from different studies on the research topic. Lastly, in step 5, the results of the articles were discussed.

3 Analysis and Discussion of Results

From the annual distribution of the publications of the 145 articles, it can be seen that the year 2020 had the highest number of articles on the subject. The higher incidence of publications in recent years was also evident, highlighting the interest and relevance of the topic. Therefore, the question 1 shown in the objective of this article was answered. It was possible to verify that among the ten countries with the highest number of articles published, China leads the position. It is noticed that the Asian continent had the highest number of countries with publications on the subject, followed by the European continent, the American continent and, finally, Oceania. The African continent was the only one not represented in this ranking. Given this information, question number 2 of the present study was answered. Therefore, it was possible to analyze that the continents with the highest waste generation are the ones that have invested the most in research on WEEE reverse logistics. This is something that can be verified through the research carried out by [10], in which they inform that China is among the countries with the highest production of e-waste in the world.

It is noticed that the publications of the 145 articles were distributed among 87 different journals. The first position in this ranking was reached by Resources, Conservation and Recycling, with 13 publications, followed by Waste Management and the Journal of Cleaner Production, both journals with 11 publications. Only these 3 journals accounted for 23.45% of the publications. The areas most interested in WEEE reverse logistics were Environmental Sciences (23.40%), followed by Engineering (21.10%), Business, Management and Accounting (10%) and Computer

Science (10%). Given this information, question 3 approached in the objective of this study was also answered. The most used keywords were Reverse Logistics, E-waste, Electronic Waste, WEEE and Recycling. Through the above data, question 4 of this study was resolved.

Among the 145 articles, the 27 most cited articles and the 21 most current articles were selected. Through these articles, it is verified that the most used research methodologies were case study (39.58%) and modeling and simulation (31.25%), these two methodologies together representing 70.83%. Although the modeling and simulation obtained 31.25% of representativeness, there is no study with the application of agent-based simulation. The vast majority of studies used mixed integer linear programming. Based on this analysis, it was possible to answer question 5 of the present study.

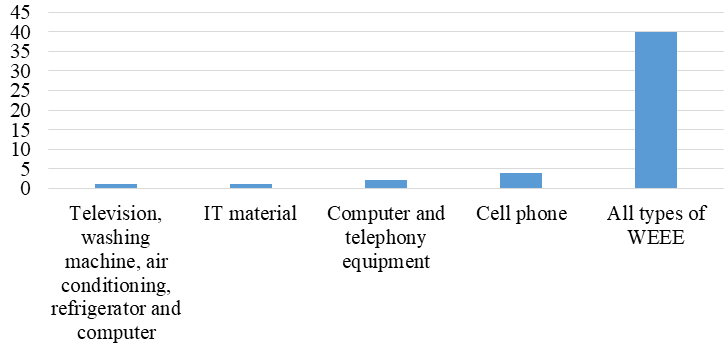

Fig. 1 - Most searched types of e-waste.

It is also noticed that most articles do not deepen the research into a type of WEEE. As per Fig. 1, 83.33% talk about All types of WEEE, 8.33% talk about Cell phone, 4.17% about Computer and telephony equipment, 2.08% about IT material and 2.08% about Television, washing machine, air conditioning, refrigerator and computer. The search for research that delimits the type of WEEE would be important due to the different compositions of EEE, volumes, weight, consumption, among other factors that affect the entire RL process, such as collection, storage, transport, costs and revenue. Thus, question 6 of the present study was answered. Below is Table 1, with the presentation of the objective and research method of the 48 articles analyzed.

Table 1. Objectives of selected articles

Author	Purpose of the study	Research method
[11]	Provide a better understanding of the forces driving WEEE management by comparing the system in Brazil and Australia.	Case study
[12]	Investigate end-user willingness to pay for recycling the WEEE they produce.	Case study
[13]	Develop an appropriate approach to recovering WEEE generated in an urban area. From locating and allocating collection centers to customer zones, and determining flow between facilities.	Modeling and simulation

[5]	Describe a reverse logistics model as a potential solution to the identified barriers and challenges.	Case study
[14]	Assess the level of consumer participation in reverse WEEE exchange programs.	Modeling and simulation
[15]	Investigate the elements that influence the behavior of returning WEEE.	Case study
[16]	Investigate the strategies used by producers and recyclers and explore their evolving behaviors under two policies	Simulation
[17]	Analyze the consumer's intention to participate in WEEE collection programs	Case study
[18]	Estimating WEEE at the micro level through a real case in Delhi, India, to help the decision maker to establish and operate an efficient reverse logistic network.	Modeling
[19]	Evaluate the environmental benefits and burdens arising from a reverse logistics system that considers a variety of WEEE.	Case study
[20]	Develop a model that maximizes profit and job opportunities, and minimizes carbon emissions in a WEEE RL network.	Modeling and simulation
[21]	Provide a set of criteria and indicators to identify the best options for urban WEEE mining, with the purpose of supporting decision-making.	Case study
[22]	Develop a new scenario-based approach that optimizes and configures a WEEE RL network, considering the uncertainty of fixed and variable costs, quantity demanded, return and quality of waste.	Modeling and simulation
[23]	Characterize the flow of WEEE in São Paulo, to verify consumer behavior.	Case study
[24]	Develop a sustainable RL network along with dismantling line balancing to analyze decisions focusing on Triple Bottom Line principles.	Modeling and simulation
[25]	Identify the main barriers to implementing the WEEE RL in Brazil and prioritize them according to the perceptions of small and medium-sized companies, consumers and the Brazilian government.	Operational Research
[26]	Evaluate the viability of a sustainable RL process in the cell phone manufacturing industry in Brazil.	Case study
[27]	Understand consumer preference for WEEE collection services.	Case study
[28]	Propose an integrated collection scheme that simultaneously considers on-call and door-to-door demands.	Modeling and simulation
[29]	Formulate RL performance criteria to identify the performance of informal WEEE companies.	Case study
[30]	Develop an economic model to estimate the amount of material that can be consolidated at a central recycling facility, optimizing the internal rate of return (IRR).	Modeling and simulation
[7]	To analyze the organization of formal recyclers in São Paulo.	Case study
[31]	Propose a new Best-Worst Multi-criteria (BWM) multi-criteria decision-making method for selecting third-party RL providers.	Operational Research
[32]	Assess whether the WEEE management system and current legislation in Italy are able to support the fulfillment of the targets defined by the EU with a specific focus on Collection Centers (CCs).	Case study

[33]	To study cost and demand for products and parts reusable PCs, to determine quality and quantity limits during various production periods.	Modeling and simulation
[34]	Review and analyze RL and Closed-Loop Supply Chain (CLSC) articles to identify specific issues.	Systematic literature review
[35]	Quantify the flow of WEEE that being diverted to the informal recycling system in China.	Modeling and simulation
[3]	Identify the contribution that RL can make to extending product life through facilitating reuse.	Case study
[36]	Find a model of engagement between government and intermediary companies, both formal and informal, for a sustainable purpose.	Case study
[37]	Propose a framework for analyzing and evaluating WEEE governance, inspired by the literature on WEEE, LR and environmental governance.	Action search
[38]	Identify the factors that define the management practices of an electronic waste center and the reuse of equipment.	Case study
[39]	Design a closed-loop model to manage the LR of desktop and laptop waste, assess the impact of Brazilian public policies on waste management and the social inclusion of collectors.	Modeling
[40]	Explore cell phone ownership, the reasons for hibernation and replacement, besides describing and implementing mechanisms to quantify the average period of hibernation.	Survey
[41]	Characterize the Brazilian market for WEEE RL credits and make an analogy with the carbon credits market.	Case study
[42]	Compare regulatory and non-regulatory WEEE RL situations in developing countries through the formulation of two models.	Modeling and simulation
[43]	Understand the perception and behavior of users of institutions and technical assistance in relation to WEEE in Blumenau, Brazil, in the years 2010 and 2015.	Survey
[42]	Propose a general WEEE RL model, multi-tier, multi-period with the aim of minimizing costs.	Modeling and simulation
[44]	Evaluate WEEE management system alternatives in Brazil according to economic, social and environmental performance, for implementation in Rio de Janeiro.	Operational Research
[45]	Develop strategic analyzes from the decision makers' points of view, to improve the WEEE RL implementation according to the PNRS.	Case study
[46]	Analyze and identify the factors that affect mobile phone return behavior by consumers.	Survey
[47]	Finding the ideal flow of WEEE in RL chains, so that the profit in the recycling process is as high as possible.	Modeling and simulation
[4]	Model a RL network design for the case in Turkey, including different scenarios, each based on different collected amounts of WEEE.	Modeling and simulation
[48]	Analyze the potential for creating green demand in the consumer market, in order to trigger and strengthen the will of companies to develop a continuous improvement approach in ecologically correct processes.	Case study
[49]	Obtain estimates of the generation rates of five types of e-waste in Hong Kong.	Survey

[50]	To quantify the cost of managing WEEE in Greece, proposing WEEE volume scenarios for the development of a reverse logistics network.	Operational Research
[51]	Defining the ideal location for a WEEE treatment facility in Greece.	Operational Research
[52]	Present a decision support tool for policy makers and regulators in order to optimize the WEEE RL network.	Modeling and simulation
[53]	Solve an integrated problem of locating and configuring WEEE recycling facilities.	Modeling and simulation

From reading the articles, it was possible to classify them according to the theme, thus 6 main thematic groups were identified (see Fig. 2).

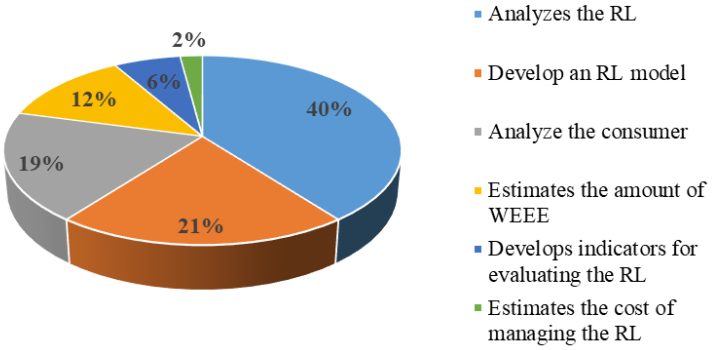

Fig. 2- Application types in the studies.

For the type of study Analyzes the RL [25] applied the Multicriteria Decision Aid approach (MCDA), through questionnaires with the aim of identifying the main barriers to the implementation of the electronic waste RL in Brazil. Already [44] used the MCDA in conjunction with the Life Cycle Assessment (LCA) to evaluate WEEE management system alternatives in Brazil according to the Three Bottom Line. [53] used the mixed integer linear programing (MIP) to solve an integrated problem of location for e-waste recycling.

For the type of study Develop an RL model [20] used the MATLAB coding tool, in order to develop a model that maximizes profit and job opportunities, and minimizes carbon emissions. [22] employed Monte Carlo simulation to analyze a new scenario-based approach in order to optimize and configure an electronic reverse logistics network considering the uncertainty associated with fixed and variable costs, the amount of demand and return, and the quality of returned products. Then, the ANOVA test was performed to statistically verify the model.

As for the study type Analyze the consumer, [12] used the theory of planned behavior (TPB). The partial least square path modeling (PLSPM) approach was employed to determine the effect of various factors, such as attitude, subjective norms, perceived behavioral control, intent, environmental concerns, and awareness of consequences, on

which the final consumer may have to pay for the recycling of e-waste. [15] used the theory of planned behavior (TPB) to investigate the elements that influence the behavior of returning WEEE. Thus, question 7 of the present study was answered.

To arrive at the answer to the last question, number 8, existing and proposed gaps in the articles studied were analyzed. According to [12], future research should further explore the concept of shared responsibility (both financial and non-financial) across different cultural contexts to improve understanding of the topic. [15] already believes that research should be done on the role of a variety of other relevant constructs, for example, participation, trust and values, which can operate as moderators or mediators between the various elements of the model.

4 Conclusions

We concluded that, although reverse logistics of WEEE is much debated by the academic community, with a higher incidence of publications in recent years, the number of studies is still small. To start a search on the subject, it is recommended to use keywords such as Reverse Logistics, E-waste, Electronic Waste, WEEE and Sustainability, as they were the most used ones in the analyzed articles.

We found that China leads the country with the highest number of articles published on WEEE RL, followed by Brazil, Turkey and Indonesia. This is consistent with the level of e-waste production in the country, once China is among the highest e-waste producing countries in the world. It was possible to notice that the Asian continent had a greater number of countries with publications on the subject. Therefore, it is evident that larger producers invest more in research in order to solve the problem.

The research methodologies most used in the articles were the case study (39.58%), modeling and simulation (31.25%), that is, these two methodologies together represent 70.83%. Although modeling and simulation reached the second position, articles using the agent-based simulation tool were not identified in the analyzed publications. The most common researches were focused on the consumer, for example, analysis of consumer participation in the WEEE collection program, or investigation of the elements that influence the behavior of returning WEEE, or understanding consumers' preference for WEEE collection services, among others.

We also conclude that one of the factors that hinders the implementation of the reverse logistics process is the unpredictability of the amount of waste that can be collected, and some reasons for this are the absence of consumer awareness of collection and recycling opportunities, as well as the population's tendency to keep used items at home.

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