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VALUE CHAIN INTEGRATION FOR E-WASTE MANAGEMENT: A SYSTEM DYNAMICS APPROACH

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ABSTRACT: The increasing of electronic waste (e-waste) generation around the world is the result of population growth and the demand for technological solutions to carry out everyday activities. It is estimated that more than 50 million tons of e-waste are generated annually across the globe. Valuable substances and also dangerous materials can be found in e-waste, requiring the development of public policies and business strategies for their management and avoid environmental, social and economic challenges. Therefore, recycling materials from secondary sources can represent a solution for managing this type of waste. In this context, urban mining becomes a tool for the circular economy, recovering materials from secondary resources, such as e-waste, promoting the comprehensive utilization of resources and the development of the circular economy. This study evaluates the e-waste integration value chain through the elaboration of cause-and-effect diagrams based on system dynamics, considering business models and regulator structures, to obtain a systematic view of the intervening (positive and negative) factors in the integrated e-waste management chain. The outcomes derived from this model demonstrate that secondary materials, when reintegrated into new production cycles, contribute to reducing the reliance on natural resource extraction and, preventing impacts in resources supplying.

Keywords: Urban Mining; Electrical and Electronic Waste; Closed Loop; Systems Dynamics.

1. INTRODUCTION

The rapid population growth, coupled with high consumption rates, demanded the production of new products in recent years, including electronic devices. Therefore, the generation of electronic waste (e-waste) reached the rate of 3% to 5% per year (CUCCHIELLA et al., 2015). The disposal of e-waste in 2019 was estimated in 53.6 metric tons in the world, representing only 17.4% was adequate disposed (UNITED NATIONS, 2021).Thus, there is a demand for solutions that align with the country's sustainability commitment, driving the need for actions that can balance economic growth, innovation, and environmental sustainability.

The transition from a traditional linear model economy based on the use of non-renewable and finite resources with inadequate disposal to a circular economy with regeneration, reconvey and recycling systems is inevitable. The need to reduce waste and achieve economic and environmental goals **are** essential **in the** transition from a linear economy to a circular economy, **including** a strategic approach to **products and material** reuse as a fundamental principle to increase the **lifetime and alleviate the pressure to obtain natural resources**. A relatively recent topic is the integration of waste as resources or secondary materials into different supply chains, which can be made possible through tools such as urban mining (UM), regarding the recovery of a variety of waste streams, including those from landfills, construction, and demolition (building stocks), e-waste, end-of-life vehicles, and solid waste (ARORA et al., 2017).

However, circular economy (CE) and urban mining of e-waste are integrated in the objective of reducing the negative impact of these wastes on the environment and human health through improper disposal (WEETMAN, 2019). Thus, exploring of secondary materials requires the establishment of laws, specific standards and decrees for the management of electronic waste in the production chain, enabling the formation of new businesses, driven by significant efforts, including collaboration between different regions at macro (city and state, national, regional, and municipal policies) and micro (organizational, consumer, product) levels (GUARNIERI, 2020).

Nowadays, 78 countries have some form of regulation about e-waste (BALDÉ et al., 2017; FORTI et al., 2020) and 189 countries have signed the Basel Convention on the control of transboundary movements of hazardous waste and its final disposal, into force in 1992 (FORTI et al., 2020). In case of Brazil, the fifth largest generator of e-waste, being the leader in Latin America. In global terms, according to The Global E-waste Monitor 2020, 53 million tons of waste of this type is generated per year. Even with the issue on the agenda worldwide, Brazil still lacks specific legislation regarding electronic waste, and only in 2010 did the country establish the Brazilian Police on Solid Waste. through Law 12,305, which instituted shared responsibility for the life cycle of products, consisting of a set of actions coordinated by producers and traders, importers, and distributors, consumers and those responsible for cleaning services and solid waste management to reduce the volume of generated waste and minimize the impacts on public health and the quality of the environment (BRAZIL, 2010).

National and international regulatory mechanisms play a fundamental role in mobilizing actors involved in managing the e-waste reverse chain. In 2019, the Sector Agreement for the Implementation of the Reverse Logistics System for Household Appliances and their Components was signed by the federal government, producers, distributors, and the National Electronic Equipment Waste Manager - Green Eletron (BRAZIL, 2019). In 2020, Decree 10,240 regulated the implementation of the reverse logistics system for electric and electronic domestic appliances and their components.

2. METHODOLOGY

This study consists of an exploratory and descriptive approach, considering the importance of urban mining for the proper disposal of e-waste from the perspective of circular economy, through an approach guided using a structured and causal system dynamics model, presenting a possible solution for the circularity of electronic waste, coordinating production and consumption systems in closed circuits.

Thus, it becomes possible to create new markets through synergies between industries (recyclers and producers) and the sharing of products/waste, the exchange of secondary materials for use as production inputs and the construction of closed production cycles. Business models and regulatory structures are considered to obtain a systematic view of factors affecting (positive and negative) the integrated e-waste management chain. For the construction of a causal loop model (closed loop), following the principles of CE to maximize the circularity of materials and that represents the situation to be studied, using the Vensim PLE software.

The systems dynamics (SD) conceptual model establishes a link between the variables that will be analyzed and any change in one of these variables affects one or more variables, through their flows in a dynamic way. Within SD, there are feedback processes, where each action produces a reaction in the system, changing the state of this system (STERMAN et al., 2015). Modeling through system dynamics is a tool capable of understanding the complex interactions within a circular economy, making it possible to simulate different scenarios and predict the impacts of different interventions.

To develop the elaboration of the causal model, it is necessary to define some steps, such as: identification of agents, structuring of relationships between agents, identification of factors that influence the system and data collection. By modeling material and resource flows, we can identify potential inefficiencies and design more effective circular systems.

The choice of SD as part of the methodology of this study was due to the possibility of analyzing the functioning dynamics of the links that involve this chain through qualitative analyzes (through the cause and effect diagram) from the perspective of the principles of the circular economy . It is worth mentioning that the system dynamics methodology allows the simulation and creation of scenarios that enable the prospecting and anticipation of desired futures. These circular cause and effect loop (feedback) diagrams allow analyzing the relationships between the variables of a system while the stock and flow models represent, quantitatively, the cause and effect relationship (FREITAS et al., 2022).

3. RESULTS AND DISCUSSION

The recovery and insertion of secondary materials in supply chains as an alternative solution for e-waste management can be an important contribution to minimize impacts caused by incorrect disposal and reduce uncertainty in material supplying, by keeping products and materials in use, and regenerating natural systems. In the proposed model (Figure 1) it is possible to identify the flows and stocks related to the management of e-waste in Brazil. Both reuse, reconditioning, and repair alternatives, as well as recycling solutions, contribute to reducing the pressure for the extraction of natural resources. In some alternatives, increasing useful life is prioritized, while recycling seeks to recover secondary materials, mitigating the impact of potentially dangerous materials.

Electronic waste contains both valuable materials such as gold, silver, palladium, and platinum, as well as dangerous substances such as chromium, lead, mercury, and cadmium. And the processes represented in the causal diagram represent an important point in the basis for the proposal for managing electronic waste, enabling a systemic view of the entire process, bringing understanding of all the links involved in the electronic waste management chain.

The increase in population, constant technological advances and planned obsolescence make the life cycle of EEE shorter, causing an increase in the generation of e-waste. However, the appropriate management of e-waste is not limited to these factors, but also in relation to cultural influence, whose main factor is perceived obsolescence. The consumer needs to be aware of their part within the value chain, which involves not only conscious consumption, but also the responsibility to remain with the product while it is still useful.

The closed loop diagram was intended to form a direct and coordinated relationship between all activities (production, materials manufacturing and distribution) and include informal activities focusing on e-waste, such as informal collectors included due to collection of used products, incorrect handling and possibility of contamination. There is a need to integrate the formal and informal sectors, as the latter is responsible for a large part of the collection and treatment. There needs to be synergy between national governments, society and private organizations, to enable properly correct recycling of e-waste, such as: infrastructures, raising awareness among consumers, qualifying the workforce

It is possible to see that the two “Development of environmental regulations” and “Market expansion” is a shadow variable, referring to another variable defined elsewhere, to reduce confusion and increase clarity. The model developed consolidated aspects related to the use of secondary materials as a productive institution, structuring a closed cycle and highlighting the integration of agents and the value chain through system dynamics (FREITAS et al., 2022).

In the diagram it is possible to see two variables, co-product, and by-product. The co-product is the product that appears as joint production in the production of electrical and electronic equipment (EEE). This co-product can be good and marketable, unlike a by-product which is waste and mostly discarded.

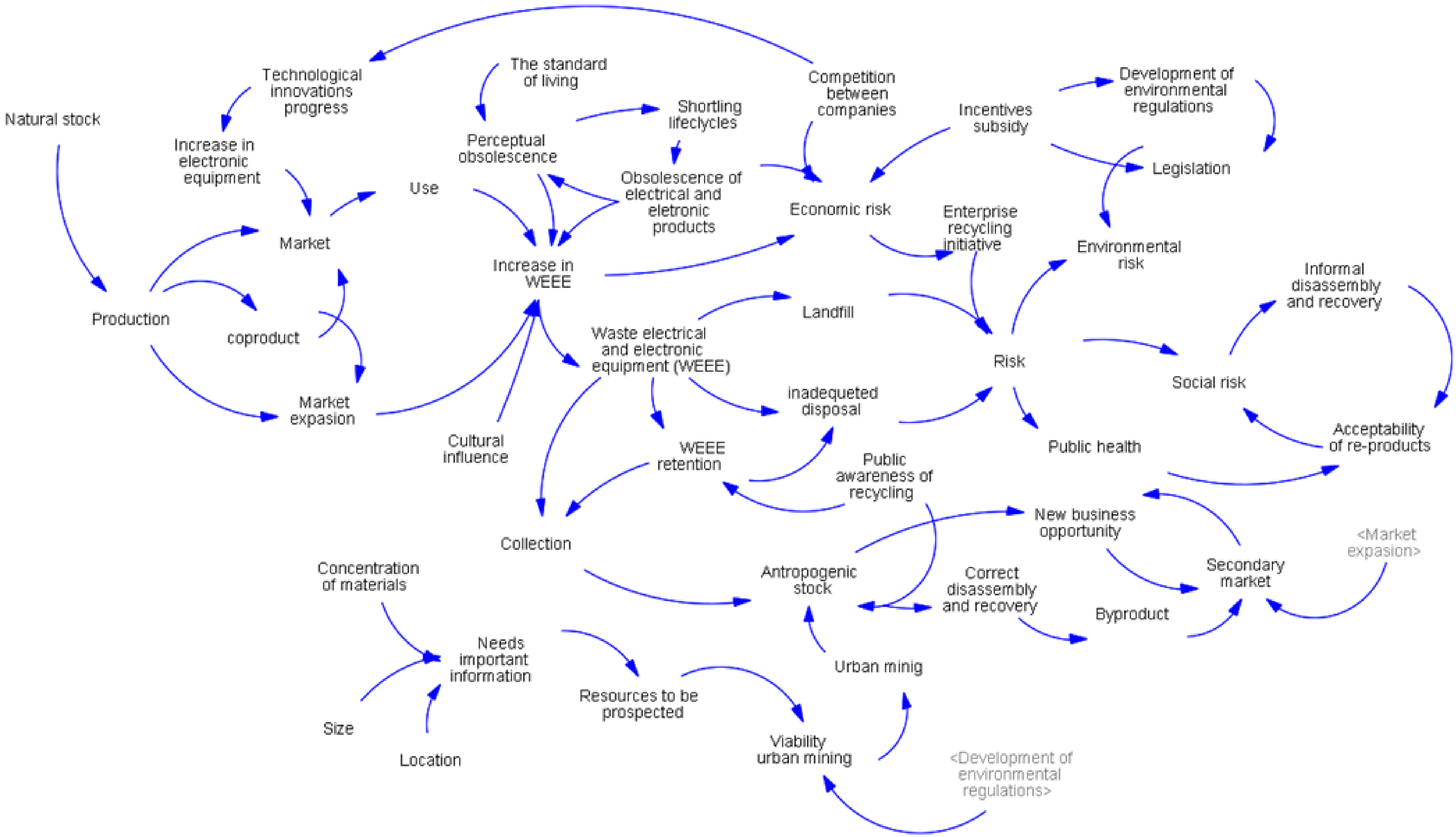

Figure 1: Closed loop diagram of value chain agents of e-waste.

Regarding economic aspects, some companies are solely concerned with profit and competition, with the aim of producing only to meet consumer demand, failing to worry about the amount of EEE on the market and the amount of waste of this type that will be generated.

These companies no longer worry about recycling activities or producing high quality recycled materials and the participation of all links in this value chain is an important strategy for the progress of other dimensions that interact with this economic dimension, such as impact and the magnitude that this sector can exert for improvements in the environmental aspect, such as the development of new specific legislation for the sector.

The influences of environmental legislation on system flows aim to promote environmental sustainability, considering the appropriate use of natural resources and the disposal of used products, enabling the consolidation of urban mining as a circular economy tool. Although the technologies necessary to comply with the PNRS are available in Brazil, the lack of integrated management and specific regulations that create opportunities to rescue and increase the value incorporated into waste, taking advantage of it before it reaches landfills, are still challenges that remain practically the same since the creation of the PNRS.

4. CONCLUSIONS

The contribution of this work is to use the causal dynamic model to understand the agents that are part of the e-waste value chain and the interaction between them, observing not only the significance of the factors that exert influence, but the specific characteristics of these systems (availability of natural resources, inadequate disposal, etc.) as well as the impact and magnitude of these interactions.

Urban mining can reduce the existing dependence on the extraction of natural raw materials and assisting the circular economy in the management of waste generated at the end of production processes and that held by the consumer. Therefore, MU can be a potential source for the recovery of valuable and hazardous materials, which can be prospected for obtaining, revaluing and reintroducing secondary raw materials. However, for urban mining to be considered viable, there must be significant information, such as: location, size, concentration of materials and resources to be prospected. It is important to highlight that the methodology used contributed to identifying potential synergies between recyclers and producers, encouraging integration between the links in the e-waste chain, associated with new strategies to encourage the use of residual inputs.

The mining urban could be to help adequate e-waste management, reduces generation, reuses, and recycles waste contributes to achieve the goals of Agenda 21 and the Sustainable Development Goals (SDGs) of Agenda 2030. The issue of electronic waste is related to several SDGs (11, 8, 6, and SDG 12 (Responsible production and consumption), which highlights in goal 12.5 the reduction of waste generation, preventing, reducing, recycling and **r**eusing materials.

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