Modeling the Dynamics of urban mining E-Waste in the cities: A System Dynamics Perspective of Rio de Janeiro's Case

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Abstract. Electronic devices such as smartphones are becoming obsolete faster and faster due to growing technological advances. Coupled with the increased consumption of these electronics is the improper disposal of e-waste, discarding valuable metals such as gold and silver into the trash every day, making it a global problem due to its exponential growth. Urban mining has emerged as a proposal to change the current production cycle, from producing, and discarding, to a model where part of the discarded resources can be reused, remodeled, and returned to the production cycle. This paper proposes a systemic vision using System Dynamics to understand the system's structure, relationships between its variables, behaviors, and feedback loops. Based on 34 variables selected from literature, the Causal Loop Diagram was constructed, indicating the existence of five feedback loops (one of which is equilibrium, and four of which are reinforcements), aiming to support the effectiveness of future strategies for enabling Urban Mining of e-waste generated by smartphones in the city of Rio de Janeiro. Limitations inherent in the understanding of the e-waste generation system point to future opportunities of research that could feeds back into the model with data from real-world approaches, contributing to the solution of the problem and then reinforcing the importance of this research for economy, society, and environment.

Keywords: E-waste, Urban Mining, System Dynamics.

1 Introduction

The expansion of a nation's economy can be gauged by fluctuations in the activities across all its sectors (services, industry, agriculture, commerce, etc.) and quantified as its GDP (Gross Domestic Product). Generally, heightened productivity correlates with increased consumption of natural resources, consequently resulting in a greater volume of products discarded as waste after consumption. While economic growth typically signifies advancements in fulfilling essential needs for all (such as infrastructure, energy, housing, and services), it's plausible that certain sectors already satisfy present demands, albeit with uneven distribution and disparities. Nevertheless, the social and ecological expenses associated with this sought-after economic expansion are not factored into GDP calculations, potentially leading to distortions in the outcomes obtained [1].

Electronic waste, also known as e-waste in this paper, has become the fastest-growing waste stream globally over the past decade, mirroring the exponential growth of technological advancements. Approximately 30 to 50 million tons of e-waste are produced annually worldwide, with an estimated annual growth rate ranging from 3 to 5%. Projections for the annual generation of e-waste portray a challenging scenario. In a publication by the Organization for Economic Cooperation and Development (OECD), forecasts range from an approximate generation of 50 million tons by 2018 to 120 million tons by 2050 whilst projections regarding the global use of raw materials also indicate a high rate of resource extraction, doubling in level by the year 2060, if nothing is done about it [2].

Urban mining has emerged as a proposal to shift the current production cycle, which is based on transformation, production, and disposal, towards a model focused on reducing the demand for production-oriented resources. This shift is possible because part of the discarded resources can be reused and reintegrated into the production cycle. Urban mining entails the recirculation of products in the post-consumption phase as secondary raw materials, aiming to address environmental, social, and economic impacts in support of sustainable development [3].

From the standpoint of System Dynamics, the issue of e-waste generation and accumulation serves as a prime example of the inherent complexity within social and economic systems. E-waste embodies this complexity, involving numerous interconnected factors and intricate dynamics with feedback loops [4]. A primary complexity surrounding the e-waste problem is the absence of an efficient collection and recycling system. In numerous nations, e-waste is simply discarded in dumps or landfills, and the lack of economic incentives for recycling electronic components results in excessive and unnecessary disposal of these materials. Another facet of the issue is the swift technological obsolescence of electronic equipment, particularly noticeable in smaller devices like tablets and smartphones [5].

The general objective of this study is to provide an understanding of the systemic problem of the accumulation of e-waste in the city of Rio de Janeiro and how it might be related to the urban mining approach success, using the resources of System Dynamics and the creation of Causal Loop Diagrams.

2 Literature review and hypotheses development

2.1 System Dynamics

System dynamics originally emerged in 1961 with the publication of the book "Industrial Dynamics", which presented a method of exploring, understanding, and seeking to improve industrial systems [6].

An important part of understanding a given system is observing what reactions are triggered by certain actions taken and what their possible outcomes are. Unlike the linear construction maintained through event-oriented thinking (problem x solution), the feedback perspective offers a circular view, starting from a problem, arriving at a solution and this then impacting on the problem initially defined. The circular perspective presented by the concept of feedback proposes that problems are not just random, unpredictable, and uncontrollable events, but rather that they are the consequences of the accumulated effects of previous intentional actions and/or decisions, so that such problems are in fact hidden "side effects"[6], [7].

The feedback structures dictate the behavioral patterns of the system, which are essential components of the systemic approach and inform efficient solution methods for systemic issues. Understanding a system's behavior necessitates a thorough examination of its variables and their temporal changes. Through analysis and identification of a system's behavior, it becomes feasible to pinpoint the underlying structure responsible for that behavior, enabling interventions capable of altering it [8].

2.2 System Dynamics and Urban Mining bibliometric review

In order to understand the scheme of approaches related to the topic, a search was carried out in the existing literature for research involving the topic of System Dynamics and urban mining, starting with the SCOPUS database in December 2023. As result 32 articles were found, producing 14 bibliometric analyses, beholding 18 journals, 105 authors, 249 variables, 10 countries and 437 keywords. Although 32 documents were located only 17 documents were available [[9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]].

Particularly noteworthy are the studies "Identifying ways of closing the metal flow loop in the global mobile phone product system: A system dynamics modeling approach," "Circular economy model of gold recovery from cell phones using system dynamics approach: a case study of India," and "An integrated method of environmental analysis and system dynamics for management of mobile phone waste in Colombia" all of which identified similarities with the present research. Regarding the presentation of the findings, only 41% of the selected studies (7) included equations and presented their respective Stock and Flow Diagrams, while 53% of them (9) provided Cause and Effect Diagrams. Highlighting the challenges encountered and the gaps in the literature, 29% of the studies (5) faced issues related to the lack of official data, indicators, and methodologies on the subject, leading them to rely on assumptions and estimates to proceed with their research. Additionally, 53% of the studies (9) did not focus on understanding the cause-and-effect relationships between variables but rather on simulating events, scenarios, and forecasts. The remaining studies either lacked proposals for further research (1), did not explore the potential of informal recycling sectors (1), or did not replicate their approaches beyond a specific subset of items within e-waste (1).

3 Methodology

3.1 System's boundaries delimitation

Defining the boundaries of a system is a fundamental step aimed at delimiting the scope and extent of the system in each study. Boundaries define which elements and which interactions are considered an integral part of the system under analysis, while distinguishing the system from its surroundings. In simpler terms, the boundaries of a system help to establish limits by saying which variables and relationships are considered relevant to the study ([26]).

In this research, the following subsystems were identified as result: Social, Smartphone market, Energy consumption, Gas emissions, E-waste generation, Economy, Public safety, Government institutions, Smartphone consumption, Sustainability, Collection and storage management, Resource management, Production technology efficiency, Recyclability and Transportation.

Based on the study of the variables and the knowledge obtained during the construction of this research, the following subsystems were placed outside the boundaries of the model: Social, Smartphone market, Energy consumption, Gas emissions, Government institutions, Resource management, Efficiency of production technology and Transportation (Fig. 1).

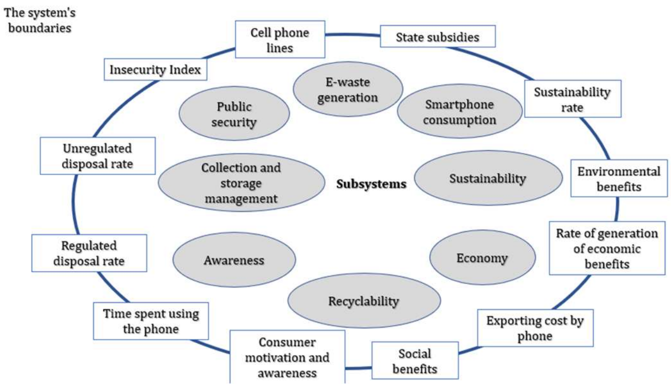

Fig. 1 - The system's boundaries

3.2 Variables Analysis

In this phase, the behavior of the system and its variables is analyzed, meticulously assessing their relevance and applicability in the development of the model under discussion. The aim of this section is to make the final selection of the variables, enabling the construction of the corresponding causal diagram, using the VENSIM PLE software in version 9.2.3.

1) Variables of the Awareness subsystem:

Consumer Motivation and Awareness - Although the aspects of consumer motivation and awareness play an important role in the problem of e-waste generation and accumulation, customer awareness from a psychological point of view is complex due to the need to understand individual motivations, which can be influenced by emotional factors such as environmental concern, feelings of guilt associated with irresponsible disposal, etc. Cultural complexity also adds to the challenges since acceptance of sustainable practices and appreciation of environmental responsibility vary considerably from culture to culture [1]. Although the difficulties of dealing with this variable have been highlighted, it has been selected as part of the system boundary.

Smartphones Discarded in Household Waste and Rate of Smartphones Sent to Landfills - the proper disposal of smartphones in household waste is a variable with a lot of potential for combating e-waste in the environment. The proper management of these devices, directing them towards recycling methods, has a positive environmental impact, significantly reducing the amount of electronic waste in landfills and mitigating environmental contamination [27]. Both variables in question were selected to build the model.

2) Variables of the Energy Consumption subsystem:

Energy Consumption and Energy Saving - The Energy Consumption subsystem was framed outside the boundaries of the system because it did not belong to the focus of the research. Its variables were therefore not selected.

3) Smartphone consumption subsystem variables:

Cell phone lines, Quality of smartphones, Useful life of smartphones, E-waste of cell phones in use at present, Time of phone use - The variables of this subsystem are of paramount importance for the construction of the model since they are able to provide a broad view of the life cycle of smartphones, measuring from the impact of e-waste generation over time and also factors aimed at the frequency of replacement, disposal and consumption habits [20]. All these variables were selected.

4) Variables of the Economy subsystem:

Import of smartphones, GDP per capita, Job creation, Demand for smartphones, Government incentives, Rate of generation of economic benefits, Sales of cell phones, Export cost per phone, Price per unit of consumer electronics - These variables are entirely linked to smartphone consumption, since they directly impact the behavior of supply and demand, as well as their consequences[17]. All economic variables were selected.

5) Production technology efficiency subsystem variables:

Household Rate 1, Household Rate 2, Manufacturing Rate, Total Cost of Refurbishment, Manufacturing Costs and Telephone Hibernation - The Production Technology Efficiency subsystem was framed outside the boundaries of the system because they did not belong to the focus of the research. Its variables were therefore not selected.

6) Gas emissions subsystem variables:

CO^2 Emission and Reduction of CO^2 Emissions - The Gas Emissions subsystem was framed outside the boundaries of the system because it did not belong to the focus of the research. Its variables were therefore not selected.

7) Resource management subsystem variables:

Demand for gold, Resource exploitation, Demand factor in metric tons, Revenues from recycled gold, Gold reserve, Gold reserve conversion rate, Gold extraction rate from e-waste, Gold reserve variation rate, Metal recovery cost per phone, Copper mass per phone, Gold mass per phone, Palladium mass per phone, Silver mass per phone, Silver price per gram, Copper price per gram, Gold price per gram, Palladium price per gram, Gold recovery rate by recyclers in developed countries, Gold recovery rate by recyclers in underdeveloped countries - The Resource Management subsystem was placed outside the system's limits because it was not the focus of the research. Its variables were therefore not selected.

8) Variables of the Cell phone e-waste generation subsystem:

Cell phone e-waste generation and e-waste generation rate - The Cell phone e-waste generation subsystem is the main subsystem contained in the model, since the generation of e-waste is what dictates the flow that must be dealt with by urban mining, i.e. all other actions and plans to be considered in the urban mining process must direct their efforts towards an e-waste generation that is adequate to the capacity to recover/generate value by recirculating them [3], [28]. With this, its variables were selected.

9) Collection and storage management subsystem variables:

Collection Sector Capacity, Collection Efficiency of the Organized Sector, Unregulated Disposal Rate, Regulated Disposal Rate, Rate of e-waste sent for refurbishment and Cost of collection by telephone - The Collection and Storage Management subsystem influences the operational flow, acting in the classification, separation and processing of the valuable materials present in discarded electronic devices, which is crucial for the viability of urban mining of the e-waste generated [15], [29]. All the variables in this subsystem were selected.

10) Variables of the Government Institutions subsystem:

Institutions and Incentive Costs - The Government Institutions subsystem was placed outside the boundaries of the system because it did not belong to the focus of the research. Its variables were therefore not selected.

11) Smartphone market subsystem variables:

Market concentration, Promotional packages - The Smartphone markets subsystem was placed outside the system's boundaries as it did not belong to the research focus. Its variables were therefore not selected.

12) Recyclability subsystem variables:

Recycling rate, Cell phone refurbishment rate, Reuse rate, Refurbishment cost per phone - The variables that make up the Recyclability subsystem are anchored to the success of urban mining, since they are linked to the volume of valuable resources extracted, as well as the efficiency of extracting and recirculating them [3], [30]. All the Recyclability variables were selected.

13) Public security subsystem variables:

Insecurity Index, Smartphone theft - The Public Security subsystem impacts on variables linked to the demand for new smartphones and can be responsible for either an increase or decrease in consumption, whether this is based on the need to purchase new items or the rendering useless of stolen devices through security actions such as device locks. As this study simulates a system located in a large metropolis, security concerns cannot be overlooked [20]. All variables from the Public Safety subsystem were selected.

14) Variables from the Social subsystem:

Social circle, Population increase - The Social subsystem was placed outside the boundaries of the system because it does not belong to the focus of the research. Its variables were therefore not selected.

15) Sustainability subsystem variables:

Environmental benefits, Social benefits, Sustainability rate - The Sustainability subsystem has all the variables kept within the boundaries of the system, so they will only be selected so that their complementary effects on the other relationships can be studied, unlike the other variables which have more complete unfolding and analyses. All the variables in the Sustainability subsystem were selected.

16) Transportation subsystem variables:

Accessibility of Collection Paths - The Transportation subsystem was placed outside the boundaries of the system because it did not belong to the focus of the research. Its variables were therefore not selected.

After establishing the boundaries of the system and critically analyzing the subsystems and their respective variables, 34 variables were selected for the construction of the Causal Loop Diagram (Fig. 2).

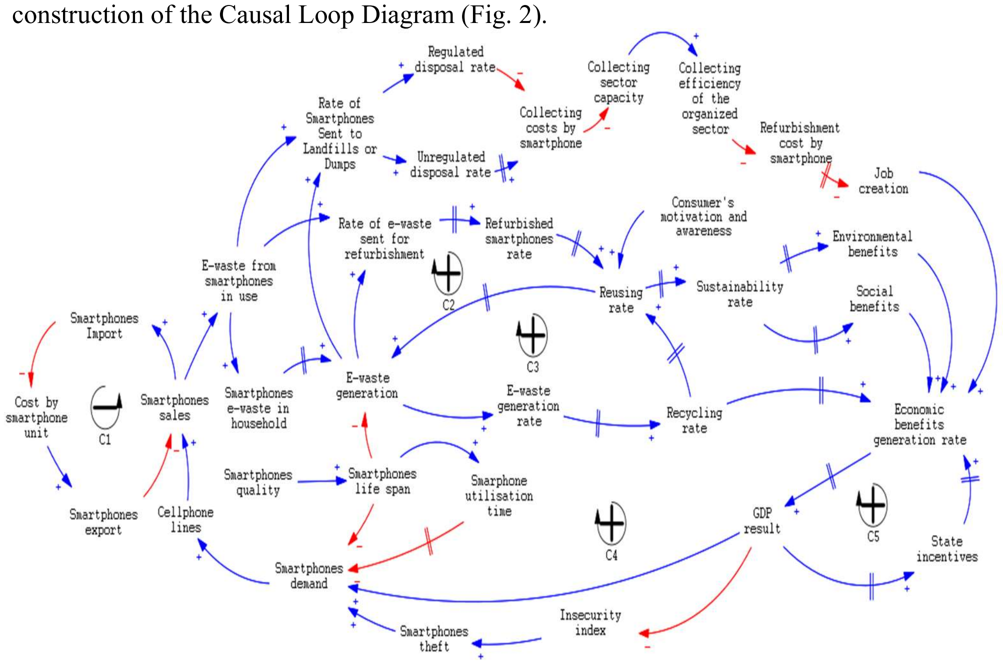

Fig. 2 - Urban Mining Causal Loop Diagram.

3.3 Causal Loop Diagram Analysis

Once the causal loop diagram has been established, the behavior of the system is observed, as well as the other relationships maintained between the variables and their respective feedback loops. As mentioned in all the papers found in the literature, the e-waste generation system points to a behavior of exponential growth, which lends urgency to the issue, given the complexity of solving the problem.

Understanding the interactions established between the variables makes it easier to identify the feedback patterns present in the system. The reinforcing feedback loop is characterized by strengthening the directions of change underway in the system, which can result in spirals of positive or negative effects, depending on the context in which they occur. On the other hand, the balancing feedback loop is characterized by counteracting, reversing, or neutralizing the transformation trends underway within the system, with the aim of re-establishing a state of stability [7].

The 'C1' feedback loop was established among the relationship between cell phone sales and their respective import and export strategies. This feedback loop tends towards equilibrium, with cell phone sales demanding more smartphone imports. More imported products lead to more margin for negotiation and, as a result, a reduction in the price per unit of electrical and electronic goods. The reduction in prices makes it possible for other interested importers to offer their products, and with these items being exported there are costs anchored to their volume. The same costs dictate the rules on strategies for maintaining sales in the national territory or not (cell phone sales), thus feeding back into the whole cycle. Although important for understanding the country's trade relations and their impact on Rio de Janeiro, the 'C1' feedback loop has a natural equilibrium behavior and is closely related to fluctuations in the national and global economy and is not responsible for the overall behavior of the system (exponential growth).

Feedback loops "C2" and "C3" refer to the e-waste generated by smartphones in the post-consumption phase, which is then remodeled and prepared to be consumed on the market once again. These reinforcing feedback loops play an important role in the system studied and should be considered for any adoption of urban e-waste mining strategies, as they can provide a reprieve in the accumulation of generated e-waste. Although this extension does not solve the problem, the time gained in the remodeling operation can serve to slow down the flow while other value generation strategies evolve.

The "C4" feedback loop is the most important set of relationships in the e-waste accumulation system in the city of Rio de Janeiro. This reinforcement cycle was located by analyzing all the existing relationships in the system, as well as all the feedback loops maintained between them, thus observing the exponential growth behavior, maintained from the increase in GDP and the consequent increase in consumption, which, by not having adequate disposal in the post-consumption phase, does not have an action to delay the generation of e-waste and reuse it by generating value and returning it to society.

Although the "C4" feedback loop presents a holistic view of the problem, strategies aimed solely at it would not be enough to solve the problem.

The "C5" feedback loop represents the reinforcing relationship established between government incentives aimed at making urban mining viable, which, by generating economic benefits, have a positive influence on GDP, which, by making these incentives viable, feeds back into them. This feedback cycle has a focus on the effects of government incentives that are not immediate and are represented as a delayed relationship.

4 Model critical analysis

The inherent complexity of systems modeling means that every model is a simplification of reality. When creating a model, it is necessary to decide which aspects of the system will be included and which will be omitted, given the impossibility of representing all the details and interactions of a complex real-world system [4].

Simplifying a system can result in significant limitations in the models. As a result, models may not adequately capture certain aspects, leading to inaccurate predictions or results that do not fully reflect actual behavior. In addition, simplification can introduce errors and omissions into models, compromising their validity and reliability [31].

The behaviors observed in "C2" and "C3" adopted premises of recyclability, remodeling, and reuse existing in the literature [14], [29], but we disregarded technological, industrial, and chemical advances, as well as unconventional approaches that may be adopted in the future not only for dismantling but also for separating and extracting valuable components. These factors could influence the behavior of "C2" and "C3" not only by further slowing down the process of e-waste accumulation in nature but also by attracting new enterprises focused on this type of activity. This could lead to new behaviors in the feedback loops, the creation of new relationships, and the arrival of new variables.

The behavior of the "C4" feedback cycle corresponded to the main premise of GDP increasing the volume of smartphone consumption and consequently increasing their disposal in the post-consumption phase, but the emergence of new consumer trends that could somehow result in reduced demand for smartphones even with the good progress of the economy was disregarded. The arrival of new technologies that could exclude the use of smartphones was also disregarded in this model. These and other examples of factors external to the relationships maintained in the system were disregarded during the creation of the model.

The behavior of feedback loop "C5" considered GDP to be an enabler for maintaining government incentives, but the arrival of a new mental model that prioritizes concern with the generation and accumulation of e-waste could put government efforts on a par with areas such as education, health, public safety, and others currently considered a priority. This change in mentality would lead to continuous investment and, therefore, a greater return in economic benefits. The arrival of an immediate mental model in government plans could also alter the bureaucratic delay of long-term initiatives, shifting to benefits returning more quickly and effectively. Another factor not mentioned is political motivation. Given the complexity of political motivations in Brazil, they were not considered in the discussion.

5 Results and discussions

While GDP is used as the main indicator of economic progress, its exclusion of social and ecological costs can distort reality. The growing volume of e-waste, particularly that produced by smartphones, highlights the urgency of adopting more sustainable approaches in the economy. It is necessary to consider not only the increase in productive activities, but also the impacts associated with natural resources and waste disposal, with a view to more balanced and resilient development for future generations.

The disproportion between e-waste disposal and the ability to generate value from the valuable components contained in smartphones represents not only a risk to the environment and human health, but also a loss of resources and opportunity if nothing is done.

From the perspective of System Dynamics, the representative model of the e-waste generation system in the city of Rio De Janeiro showed the complexity maintained between the study variables and the non-intuitive behaviors about the problem, corroborating existing studies in the literature in the affirmation that it is a problem of exponential growth. During the analysis of the model, five feedback loops were identified, resulting in a more assertive view of the cause-and-effect relationships maintained in the system that can be managed for the successful adoption of Urban Mining, making it possible to attack the problem from a holistic view to an individual approach for each subsystem and its respective variables.

This research makes it possible to identify critical points throughout the life cycle of smartphone devices, from their marketing to their disposal, highlighting the environmental, economic, and social impacts. By constructing the Causal Loop Diagram, a robust analytical framework, this study turns its efforts to assisting decision-making on more effective e-waste management policies and practices, promoting the adoption of sustainable solutions, adding value to society, the environment, and the economy.

In addition, the production of this research faced difficulties in obtaining data not only on the post-consumption phase of smartphones, but also on urban mining practices, as this is a relatively new topic with few documents addressing the problem in a systemic way (17). It is also worth mentioning the author's difficulty in recreating his own mental models, moving from linear to systemic approaches, which allowed him to enrich his world view of other problems and situations in his professional career and personal life.

As a suggestion for future research, it is recommended that the model be fed back by analyzing Urban Mining in the real world and its developments, with the aim of including all variables and relationships that have not been included in the Causal Loop Diagram at this initial stage.

Another suggestion for future research is to carry out a simulation of scenarios (using the VENSIM PLE software version 9.2.3) for the feasibility of Urban Mining in the city of Rio de Janeiro once official data has been provided to enable the model to be carried out.

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