Reverse Logistics Analysis on Household Electronic Waste Management Using System Dynamics Simulation Approach

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Abstract. E-waste is the fastest-growing type of waste in the world. The formal sector can play a role in managing waste according to environmental standards and minimizing the risk of fraction recovery with supporting facilities. However, the formal sector of e-waste management simply cannot compete with its informal sector, which has a dominant role in Indonesia. This study aims to identify what factors influence formal sector e-waste management, how it is currently performing, and to design better policies for e-waste management. This research uses the System Dynamics approach to view the complex systems of e-waste management holistically. In Jakarta, public awareness and the competition with the informal sector were the biggest challenge in this industry. The results show that public awareness-raising policies can gradually improve reverse logistics performance and economic benefits. In addition, the WEEE Processing Fund policy can double the performance and economic benefits.

1. Introduction

Approximately 45 million tons of e-waste or Waste Electrical and Electronic Equipment (WEEE) are disposed of globally each year, making this type of waste the fastest growing waste in the world with an annual growth rate of 3-5% [1]. This has become a global issue especially in developing countries where the majority do not have special regulations for e-waste management [2]. Only 2% of e-waste ends up in formal recycling programs provided by local governments, while most of the rest still goes into the informal sector [3]. Currently, Indonesia only has a few numbers of licensed e-waste collection and recycling companies, causing the informal sector to play a bigger role with its door-to-door scheme [4][5]. However, workers of this sector face the risk of recovering only a fraction of the recyclable materials and valuable metals while exposing themselves and the environment to pollutants [6][7]. Unorganized activities with these risks makes the distribution of waste to a more organized sector becomes necessary [7]. The Extended Producer Responsibility (EPR) policy in Indonesia has been stated in Governmental Regulations No. 81 of 2012. However, its implementation is still voluntary and debated because it is considered detrimental to the industry.

An earlier study has shown that improving collection system has potential to promote efficient closed-loop system [8]. Increasing the efficiency of collection, refurbishment, and recycling according to standards can minimize toxic material exposure and help fulfilled the gold demand for manufacturing new products (for example cell phones) with recycled gold [7]. However, developing countries face the challenge of the informal sector playing a dominant role in collecting e-waste [5]. In this study,
interviews will be conducted to understand precisely what challenges are faced by the reverse logistics system in Jakarta.

The advancement of electronic devices and the speed at which products become obsolete [9], and the contents of e-waste that are harmful to the environment and health [10] make this issue and its management essential to note. WEEE management is a complex system consisting of manufacturers, consumers, informal processors, and formal processors [11]. This study aims to identify the factors that influence the management of e-waste, analyze the reverse logistics performance of e-waste, and formulate policy recommendations related to e-waste management in the formal sector in Jakarta (the capital city of Indonesia). It is expected that this study will provide insights concerning the reverse logistics of e-waste management system in the formal sector in Jakarta, and ways to improve its performance.

2. Method
The performance of reverse logistics of e-waste will be measured by the variables of collection rate, recycle rate, and disposed product. Furthermore, identification of structures and players in reverse logistics of electronic waste will be carried out, along with the modeling for simulation. Complex systems in reverse logistics are modeled with system dynamics, which is a method to facilitate understanding of complex systems with computer simulations to design more effective policies [12]. Causal Loop Diagram (CLD) and Stock and Flow Diagram (SFD) simulation models will be made and ran using Vensim PLE.

In this study, primary data were taken from in-depth interviews with three formal sector institutions, which are the Jakarta Environmental Agency, a collector NGO, and a waste processor company. The interviews were conducted on May 2021 for approximately 1 hour with each institution. The system dynamics for this context is modified from Ardi & Leisten’s research [5] by adopting its dissertation, the research of Chaudhary [7], and the results of interviews due to its result that had modeled and assessed the role of informal sector in the management of WEEE. This study will be focused on the formal sector due to limitations in tracking “hidden flows” of the informal sector [13], nonetheless both sectors still have similar plots [14].

3. Results and discussion

3.1. Reverse Logistics Structure
In Indonesia, the role of the formal sector is commonly carried out by local governments, either managed independently or passed over to local companies [15]. The Jakarta Environmental Agency has three methods in collecting household electronic waste, namely administrative area-based collection, e-waste pick-up services, and dozens of e-waste drop boxes spread across Jakarta’s public spaces. Once the household e-waste is collected, the waste will be stored in a warehouse, sorted, and then transported by a processing company certified by the Ministry of Environment and Forestry for further processing.

The model in this study was made under several assumptions; 1) does not take industrial and imported e-waste into account; 2) that the price of precious metal is constant; 3) stock variables beside Formal Collected Product are assumed to be zero in the beginning due to data limitation; and 4) the simulation period is 5 years from 2020 with a time step of 0.25 (quarterly) following the available data from 2019-2020 to compare the simulation results with the actual data. The CLD hypothesis was created by modifying the research of Ardi & Leisten [5] which was developed based on the results of interviews to adjust the reality. Differing from the previous study, this article did not include the dynamic of workers due to the constant number in each institution. The revenue was also modified as the processor company did not directly resale in the secondary market, therefore the revenue will come from the precious metal (economic benefit). In this model, there are 5 Reinforcing Loops and 4 Balancing Loops which describe the flow and the dynamics of the formal sector in the collection, refurbishment, and recycling activities (figure 1).
In the SFD model, e-waste will go into two out of five recovery options namely refurbishing and recycling [16]. The total amount of household e-waste or the WEEE Generation variable is estimated by entering the delay function and multiplication in the software. In this quantitative model, secondary inventory does not affect WEEE Generation, because this variable has been adequately described by multiplying the population and e-waste per capita (figure 2).

3.2. Base Case Scenario: Current Condition

Formal Collection Rate shows a decline in early 2020 (year 1), then an increase in the next period (Figure 3a). This decline is also shown in actual data (Figure 3b) due to collection restrictions in the 1st, 2nd quarter when the Large-Scale Social Restrictions was implemented in Jakarta until July. Although...
there was a decline at the beginning of the year, historical data show that the amount collected was larger than in 2019 (Figure 3b). This can be caused by the factor of electronic products becoming a necessity during the pandemic [17], which makes the demand for electronic products increase and the potential for electronic waste in the future also increases [18]. Collection from drop box in 2020 decreased due to social distancing policies but the amount of waste collected through pick-up services increased.

![Formal Collection Rate and Collected E-Waste](image)

**Figure 3.** Formal Collection Rate Base Case Scenario.

The simulation results of *Refurbishment Rate* variable shows the behavior of exponential growth (Figure 4), because in this model the waste that has been received can be directly processed for repair without going through other stages as the recycling flow. In recycling option, e-waste has gone through treatment stages such as decontamination, dismantling, and segregation. The *Recycling Rate* shows the behavior of s-shaped growth with overshoot (Figure 4), which means that there is growth and fluctuation caused by the time delay in the balancing loop [12]. In addition, based on interviews, products that have gone through the treatment process will most likely go into the disposal process rather than getting recycled. The *Economic Benefit* derived from this activity is income from the sales of precious metals contained in e-waste. The level of metal extraction is still low, which is around 2.5%, wherein the processing company observed that this activity is still carried out at the parent company located in foreign country due to more advanced facilities.

![Simulation Graphs](image)

**Figure 4.** Base Case Scenario Simulation.
3.3. Scenario 1: Increasing Public Awareness

The lack of public awareness about the importance of proper waste disposal becomes one of the reasons of the lack of e-waste collection by local governments [19]. Based on the interviews, society with upper-middle income will voluntarily release their e-waste, but those with lower income will feel more benefited if they submit their e-waste to the informal sector to get paid at an appropriate price. Although formal management channels are available in Jakarta, community participation is still low due to the high presence of the informal sector [20].

The dissemination of information can have a significant effect on consumer recycling attitudes [21]. In this scenario, the SFD model is combined with Public Awareness as a constant variable which assumed to increase 10% of the Formal Collection Percentage. This scenario results show a higher value on each key variable compared to the base scenario, although the increase is not very high (figure 5). By increasing public awareness by 10%, it increases the formal collection rate by 10.01%, formal refurbishment rate by 7.14%, recycling rate by 0.06%, disposed product by 0.05%, and economic benefit by 0.03%. The collection rate has the biggest growth than the other variables because this policy mainly aims at the downstream side, that is consumers. Although the growth moves gradually, with the increasing waste collected, the waste that can be processed properly will also increase.

![Graphs showing Scenario 1 Simulation](image)

**Figure 5.** Scenario 1 Simulation.

3.4. Scenario 2: WEEE Processing Fund Policy

Based on the interview with one of the waste processing companies, competition with the informal sector is a challenge to this industry. The formal sector has a different system, which requires testing, equipment, and standard mechanisms that make it difficult to compete with the informal sector. The WEEE Processing Fund Policy proposed that imposing fees on manufacturers and subsidies to processing companies can minimize the role of the informal sector [11]. This policy is expected to provide benefits for processing companies and have the potential to attract new formal players [11]. The results of the subsidy are assumed to be used to add facilities or increase the number of processing companies which will increase the percentage of processing. The simulation results show a significant increase in recycling, repair, and economic benefits (Figure 6). The application of this subsidy can prevent processing companies from going bankrupt [11].

The simulation showed this policy could double the refurbishment rate, recycling rate, and economic benefit. However, the collection rate and disposed product did not show significant growth. This is because the policy was aimed for the upstream side or the processor. The fees will later become a subsidy.
to assist processing companies in increasing their capacity. However, this implementation requires commitment from all parties to make it work.

![Figure 6. Scenario 2 Simulation.](image)

4. Conclusion

E-waste that continues to grow every year, especially during the pandemic (when electronics are a necessity), makes this type of waste to require special attention. The collection of e-waste can be influenced by the number of formal workers and the service programs offered to the community. Currently, the level of management is quite good, although it still has a fairly low number for household e-waste. Increasing public awareness could gradually increase the amount of collection, therefore potentially increase the formal treatment of e-waste and the economic benefit. From the upstream side, the government can apply one of the EPR concepts by imposing costs on manufacturers for each unit manufactured. This policy could help the processor company and significantly increase the amount of e-waste treated properly. Although the scenario 2 seems better, its implementation requires a relatively longer period of time than scenario 1. Addressing the issue of e-waste is a long-term task and requires collaboration from all parties involved. This research has limitations which includes only getting insight from recycling and collecting parties, using historical data in the range of 2-3 years, and the scenarios model is simplified.

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