OmniaScience

Journal of Industrial Engineering and Management
JIEM, 2024 – 17(1): 292-320 – Online ISSN: 2013-0953 – Print ISSN: 2013-8423
https://doi.org/10.3926/jiem.6651

Economic and Environmental Benefits of E-Waste Management Networks Design in Yogyakarta Province, Indonesia

Diana Puspita Sari[1*], Nur Aini Masruroh[2], Anna Maria Sri Asih[2]

[1]*Diponegoro University (Indonesia)*
[2]*Universitas Gadjah Mada (Indonesia)*

[*]*Corresponding author: dianapuspitasari@lecturer.undip.ac.id*
aini@ugm.ac.id, amsriasih@ugm.ac.id

Received: October 2023
Accepted: January 2024

Abstract:

Purpose: Electronic devices consumption, especially smartphones for communication, has increased significantly, causing the potential for electronic waste (e-waste) to increase, too. However, the high potential of this flow has yet to be matched by good waste management. This study aims to develop a management network for e-waste that collaborates formal and informal channels to provide optimal supply chain benefits in terms of economic and environmental aspects

Design/methodology/approach: This research designs an e-waste management network and builds a single-objective mathematical model considering economic and environmental aspects. This model was solved using Mixed Integer Linear Programming.

Findings: The supply chain will benefit from the proposed management network by collaborating formal and informal channels. With an incentive of 10,000 IDR, it will invite consumers and informal collectors to collect waste in formal channels. The total profit from managing e-waste supply every month from Yogyakarta Province is 5.529×10^{10} IDR with the composition, consumers 81.2%, 13.3% obtained from informal channel (collectors and repairing centers) and 2.1% for formal channels. There is an intangible profit of 3.4%. The formal channel provides more significant benefits than the informal but one requires a significant investment. This formal channel is feasible if at least 33% of the total supply goes to this channel.

Research limitations/implications: The model designed is deterministic. Therefore, it can be developed into a probabilistic model for further research to represent more real cases in the field.

Practical implications: Regulation is the factor that most influences consumers' intentions and behavior to participate in e-waste management programs. It will be able to change consumer behavior by forcing consumers to participate in e-waste collection programs. Therefore, a government regulation that organizes and supervises the implementation of the proposed management model is needed.

Social implications: Currently, the practice developing in the community is that the informal sector carries out smartphone waste management, therefore in the designs made, informal actors are still given space in waste management for the repair process and the secondhand market. Meanwhile, further processing, such as recycling, must be done through formal channels, considering the environmental impact.

Originality/value: Few studies have developed an electronic waste management model by collaborating informal and formal channels that consider economic and environmental aspects, and its implementation is organized and supervised by government regulations.

Keywords: reverse logistics, e-waste, formal, informal, mixed integer linear programming

To cite this article:

Puspita-Sari, D., Aini-Masruroh, N., & Sri-Asih, A.M. (2024). Economic and environmental benefits of e-waste management networks design in Yogyakarta province, Indonesia. *Journal of Industrial Engineering and Management*, 17(1), 292-320. https://doi.org/10.3926/jiem.6651

1. Introduction

The rapid technological and economic developments in Indonesia in the last few decades have increased the public's use of electronics (Andarani & Goto, 2014). The Global E-waste Monitor 2017 Quantities, Flows, and Resources stated that the Indonesian population produced 1.274 million tons of e-waste or 4.9 kg per capita in 2016, placing Indonesia as the ninth e-waste producer worldwide. The consumption of electronic devices, especially smartphones, increased with the coronavirus pandemic, which began at the end of 2019. During this pandemic, people have to reduce social interactions, so they have to work and study from home online. As a result, smartphone consumption experienced the highest increase of 70%, followed by laptops in the second position and personal computers at 40% and 32%, respectively (Watson, 2020). So, the smartphone is one of the electronic products with the most significant proportion of e-waste. Furthermore, this will undoubtedly impact increasing the potential for waste (Sari, Masruroh & Asih, 2021a).

However, a good waste management system has not matched this high potential for waste flow (Baldé, Forti, Gray, Kuehr & Stegmann, 2017). In developing countries, including Indonesia, e-waste management is among the most challenging problems (Arya & Kumar, 2020; Sari, Masruroh & Asih, 2021b). In Indonesia, no regulation organizes the waste collection and transportation system until the final process (Syahban, 2018a). Indonesia's current e-waste management system is still limited to informal initiatives, so the United Nations University classifies the waste management system at the lowest level. This management pattern is one of the differences between developed countries (Sutanto, Yuliandra & Pratama, 2017). Improper handling of waste is dangerous for humans and the environment (Hanisah, Kumar & Tajul, 2013) because electronic waste is one of the ozone-depleting substances (United Nation Environment Program - UNEP, 1987). Seeing the negative impact on humans and the environment caused when it is wrong in this electronic waste, there should be proper waste management procedures, one of which is by designing reverse logistics whose implementation is organized and supervised by the government regulations (Sari et al., 2021a). Furthermore, collecting and utilizing e-waste will provide economic and environmental benefits. If recycled, e-waste will generate profits because e-waste contains valuable materials (Ardente, Calero-Pastor, Mathieux & Talens-Peiró, 2015) while minimizing or eliminating waste disposed of in the environment (Ripa, Buonaurio, Mellino, Fiorentino & Ulgiati, 2014). Therefore, a reverse logistics (RL) network for electronic waste is needed. It is hoped that the electronic waste management design can reduce the environmental impact and increase the economic value of the waste (Sari et al., 2021a), therefore being able to create green supply chain management (GSCM). GSCM integrates supply chain management (SCM) with environmental management. SCM is a series of management processes, suppliers and customers. In today's global market, supply chain management is a key competitive advantage for companies (Safari, Etezadi, Moradi-Moghadam, & Fathi, 2021). GSCM aims to reduce waste and maintain environmental quality (Sugandini, Muafi, Susilowati, Siswanti & Syafri, 2020). The main focus of GSCM practice is to evaluate environmental performance according to established standards, measure product quality and environmental impact, and estimate the cost of waste from the production process (Wongthongchai & Saenchaiyathon, 2019).

Research related to RL management networks has been widely carried out in various domains, such as the design of electrical and electronic waste management networks (Tosarkani, Amin & Zolfagharinia, 2020; Doan, Amer, Lee, Phuc & Dat, 2019; Taleizadeh, Haghighi & Niaki, 2019; Messmann, Helbig, Thorenz & Tuma, 2019; John, Sridharan, Ram-Kumar & Krishnamoorthy, 2018; Tosarkani & Amin, 2018; Bal & Satoglu, 2018; Guo, J., Liu, X. & Jo, J., 2017), e-commerce products (Dutta, Mishra, Khandelwal & Katthawala, 2020), household appliance products

(Zarbakhshnia, Soleimani, Goh & Razavi, 2019), vehicles (Kuşakcı, Ayvaz, Cin & Aydın, 2019), furniture (Liao, 2018), motor vehicle tires (Banguera, Sepúlveda, Ternero, Vargas & Vásquez, 2018), construction (Rahimi & Ghezavati, 2018), and medical devices (Govindan, Paam & Abtahi, 2016). The many recent studies that have taken the object of e-waste shows that e-waste is an exciting opportunity to be raised and resolved because of the significant potential for waste. However, the waste generated is harmful to the environment. Furthermore, until now, few studies have raised this issue for the case in Indonesia. Models developed in other countries are not necessarily suitable to be applied in Indonesia, considering that waste management in Indonesia is still only informal. Research by Budijati (2016) has developed a reverse logistics management model for informal and formal channels for smartphone products, but it is still only an initiative from business actors. No regulations organize it, while the research that will be carried out is collaborating formal and informal channels with the implementation of organized and supervised management by government regulations. In addition to government regulatory factors and unintegrated routes, the reverse logistics model built (Budijati, 2016) does not provide details of the reverse logistics network model to the operational level.

Smartphone waste allows for resale (reuse), repair, and recycling. Although several studies raised electrical and electronic waste, only two researchers involved collection, repair, and recycling, namely Doan et al. (2019) and John et al. (2018), the model built have single objective. So this study will develop a single objective RL management network model, namely maximizing profits by collaborating formal and informal channels to consider smartphone products' economic and environmental aspects. The resulting environmental impacts are converted into environmental impact costs. The players involved include consumers, informal collectors, repairing centers, recycling centers, collection centers, disposal centers, secondary material markets, and secondhand markets (reuse).

This study aims to develop a management network for e-waste that collaborates formal and informal channels to provide optimal supply chain benefits in terms of economic and environmental aspects. It is considered from several reverse logistics management models. Only a few studies have developed an electronic waste management model by collaborating informal channels and formal channels that consider economic and environmental aspects, the implementation of which is organized and supervised by government regulations. However, the informal channel is still used, considering the number of players in this channel (Sari et al., 2021a).

2. Literature Review

The development of the waste management network model is completed chiefly using a mathematical model, which begins with the determination of objectives, continues with the identification of the scope, identification of constraints, and finally, the selection of the appropriate solution model. Based on the objective function of the mathematical model, some are single-objective, and some are multi-objective. For example, research by Doan et al. (2019), Kuşakcı et al. (2019), John et al. (2018), Liao (2018), Banguera et al. (2018), Alshamsi and Diabat (2017), Ayvaz, Bolat and Aydin (2015), Soleimani and Govindan (2014), Keyvanshokooh, Fattahi, Seyed-Hosseini and Tavakkoli-Moghaddam (2013), Alumur, Nickel, Saldanha-da-Gama and Verter (2012), Dat, Truc-Linh, Chou and Yu (2012) and Gomes, Barbosa-Povoa and Novais (2011) developed a single objective mathematical model. While, researchs by Dutta et al. (2020), Tosarkani et al. (2020), Taleizadeh et al. (2019), Zarbakhshnia et al. (2019), Messmann et al. (2019), Zhen, Huang and Wang (2019), Tosarkani and Amin (2018), Guo et al. (2017), Bal and Satoglu (2018), Rahimi and Ghezavati (2018), Govindan et al. (2016) and Sohrabi, Etemad and Fathi (2018) developed for a multi-objective.

The scope of supply chain players involved varies quite a bit between researchers. Research by Doan et al. (2019), John et al. (2018), Liao (2018), Soleimani and Govindan (2014), and Dat et al. (2012) involve all actors altogether, which including collection centers, sorting centers, repair centers, recycling centers, remanufacturing centers, secondary markets, and primary markets. Meanwhile, other researchers did not involve all actors. For the solution model, most use a linear model, mixed-integer linear programming (MILP), as was done by Taleizadeh et al. (2019), John et al. (2018), Banguera et al. (2018), Alshamsi and Diabat (2017), Keyvanshokooh et al. (2013), Alumur et al. (2012), Dat et al. (2012) and Gomes et al. (2011). Research by Tosarkani and Amin (2018) combine MILP with Fuzzy-Analytic Network Process (Fuzzy-ANP), Zarbakhshnia et al. (2019) and Messmann et al. (2019) combine mixed integer programming (MIP) with the epsilon constraint approach, while Doan et al. (2019) and Kuşakcı et al. (2019) using Fuzzy MILP. Bal and Satoglu (2018) used another linear model: combining goal programming with the epsilon constraint approach, and Dutta et al. (2020) used weighted goal programming. Meanwhile, the non-linear model used by Tosarkani et al. (2020), Zhen et al. (2019), Liao (2018), Rahimi and Ghezavati (2018), Govindan et al. (2016), Soleimani and Govindan (2014) and Ayvaz et al. (2015). From the mathematical model built, Doan et al. (2019) and Sohrabi et al. (2018) including the risk factors of the developed model, Taleizadeh et al. (2019) calculates the price of the recovered product, Keyvanshokooh et al. (2013) calculate the price of waste from consumers, and Guo et al. (2017) used a joint decision to build a recycling network design, this joint decision is a joint decision between the government and the company.

<table>
<tr><th rowspan="2">References</th><th colspan="10">Network</th></tr>
<tr><th>CS</th><th>IC</th><th>CC</th><th>SC</th><th>RC</th><th>RpC</th><th>RmC</th><th>DsC</th><th>SM</th><th>PM</th></tr>
<tr><td>Dutta et al. (2020)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td></td><td></td><td>√</td><td></td><td></td></tr>
<tr><td>Tosarkani et al. (2020)</td><td></td><td></td><td>√</td><td>√</td><td colspan="2">√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Doan et al. (2019)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Taleizadeh et al. (2019)</td><td></td><td></td><td>√</td><td></td><td>√</td><td></td><td>√</td><td>√</td><td>√</td><td></td></tr>
<tr><td>Zarbakhshnia et al. (2019)</td><td></td><td></td><td>√</td><td></td><td>√</td><td></td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td>Messmann et al. (2019)</td><td></td><td></td><td>√</td><td></td><td>√</td><td colspan="2">√</td><td>√</td><td></td><td></td></tr>
<tr><td>Zhen et al. (2019)</td><td></td><td></td><td>√</td><td></td><td colspan="3">√</td><td></td><td></td><td>√</td></tr>
<tr><td>Kuşakcı et al. (2019)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td colspan="2">√</td><td>√</td><td></td><td></td></tr>
<tr><td>John et al. (2018)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Liao (2018)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Banguera et al. (2018)</td><td></td><td></td><td>√</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Tosarkani & Amin (2018)</td><td></td><td></td><td>√</td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td>Guo et al. (2017)</td><td></td><td></td><td></td><td></td><td>√</td><td></td><td></td><td></td><td>√</td><td></td></tr>
<tr><td>Bal & Satoglu (2018)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td></td><td></td><td>√</td><td></td><td></td></tr>
<tr><td>Rahimi & Ghezavati (2018)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Alshamsi & Diabat (2017)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td></td><td>√</td><td>√</td><td>√</td><td></td></tr>
<tr><td>Govindan et al. (2016)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td></td><td></td><td>√</td><td></td><td></td></tr>
<tr><td>Ayvaz et al. (2015)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td><td>√</td><td></td></tr>
<tr><td>Soleimani & Govindan (2014)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Keyvanshokooh et al. (2013)</td><td></td><td></td><td>√</td><td>√</td><td colspan="3">√</td><td>√</td><td></td><td></td></tr>
<tr><td>Alumur et al. (2012)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td></td></tr>
<tr><td>Dat et al. (2012)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>Gomes et al. (2011)</td><td></td><td></td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td>This research</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td><td>√</td><td></td></tr>
</table>

CS: Consumers, IC: Informal Collector, CC: Collection Center, RC: Recycling Center, RpC: Repairing Center, RmC: Remanufacturing Center, DsC: Disposal Center, SM: Secondary Market, PM: Primary Market

Table 1. Research related to Reverse Logistics Network Development

By considering previous studies that have been done, this study tries to develop a single-objective network model, namely maximizing profits, that considers the aspects of economic benefits and environmental impacts and solves them using mixed-integer linear programming. The resulting environmental impacts are converted into environmental impact cost units to reduce the profit that will be received. The supply chain actors involved include consumers, informal collectors, collection centers, sorting centers, repairing centers, recycling centers, disposal centers, battery processing centers, secondhand markets, and second material markets. The recycling center is divided into formal and informal recycling centers. The collection center is also divided into the primary collection center and the secondary collection center. Informal collectors, repair centers, and informal recycling centers are players on the informal path. Meanwhile, the players for the formal channel are the collection center, sorting center, recycling center, disposal center, and battery processing center. The position of this research, among other studies in reverse logistics network design, can be seen in Table 1.

Several studies have shown that network design is essential in reverse logistics, which is expected to solve waste management problems. Developed countries already have waste management regulations, while most still need to be created in developing countries. This regulation will ensure that waste management practices follow the designed management model. For this reason, government regulations or policies are needed that organize the implementation of electronic product waste management (Sari et al., 2021b). Regulations are overseen by the government to minimize end-of-life effects on the environment (Agrawal, Singh & Murtaza, 2016). E-waste policies and laws will play an essential role in establishing principles and responsibilities among stakeholders (Arya & Kumar, 2020).

3. Research Methods

The completion steps start from the first step of designing the management network, and the second step is building the model structure by determining the model input, formulating a mathematical model and determining the output obtained from the developed model. The model built is a single objective model to maximize profits by considering economic and environmental aspects. The resulting environmental impacts are converted into environmental impact fees. Completion of the model built using mixed integer linear programming (MILP) optimization techniques. By Solver software from Microsoft Excel. Sensitivity analysis is carried out to determine the model's behaviour when any model parameters are changed. Sensitivity analysis will be performed by changing supply parameters. The final stage is the implementation of the results of the electronic waste management design that is suitable for application in Indonesia based on the results of the mathematical model calculations that have been carried out.

3.1. Management Network Design

The current practice is informal management, with actors including collectors, recycling, and repair centers acting as workshops and buying and selling used products. Unfortunately, informal recycling is detrimental to the environment and health. Licensed companies should recycle to minimize negative impacts, and formal channels carry out such recycling.

The development of e-waste management is carried out by building collaboration between relevant stakeholders to achieve sustainable products through informal and formal channels. This research builds a multi-echelon management network involving consumers, informal and formal channels. Informal players currently exist in informal channels carried out by individuals, including informal collectors (IC), recycling centers (IRC), and repair centers. Meanwhile, formal players are proposed in this research, most of which still need to be in the field. Formal players include collection, sorting, recycling, battery processing, and disposal centers. Consumers can go to the repair center to sell their used smartphones or collect them at a collection center. Informal collectors (IC) who get waste from consumers have been distributing it to informal recycling centers (IRC); in the model built, it is hoped that informal collectors (IC) will switch to collecting them at collection centers. The repairing center is carried out on the informal channel while starting the collection center is the beginning of the formal channel. Collection centers include primary collection centers (PCC) and secondary (SCC). Consumers, informal collectors, and repairing centers collect smartphone waste to PCC. From PCC, the local government transports to SCC. Then from SCC, a formal recycling center (FRC) will be carried out by a licensed company. The battery will be dismantled before the smartphone is recycled at the formal recycling center. Then, the battery will be processed further at the battery processing center (BPC). Finally, the remaining recycling residue and battery processing residue will be disposed of at the disposal center (DsC). Used products that do not go to the repairing center or

PCC assume that the product is discarded and goes to the informal collector. The recycling center will sell the resulting material to the secondary material market (SMM), while the repairing center will sell its products to the secondhand market (SM). The proposed management network model is shown in Figure 1.

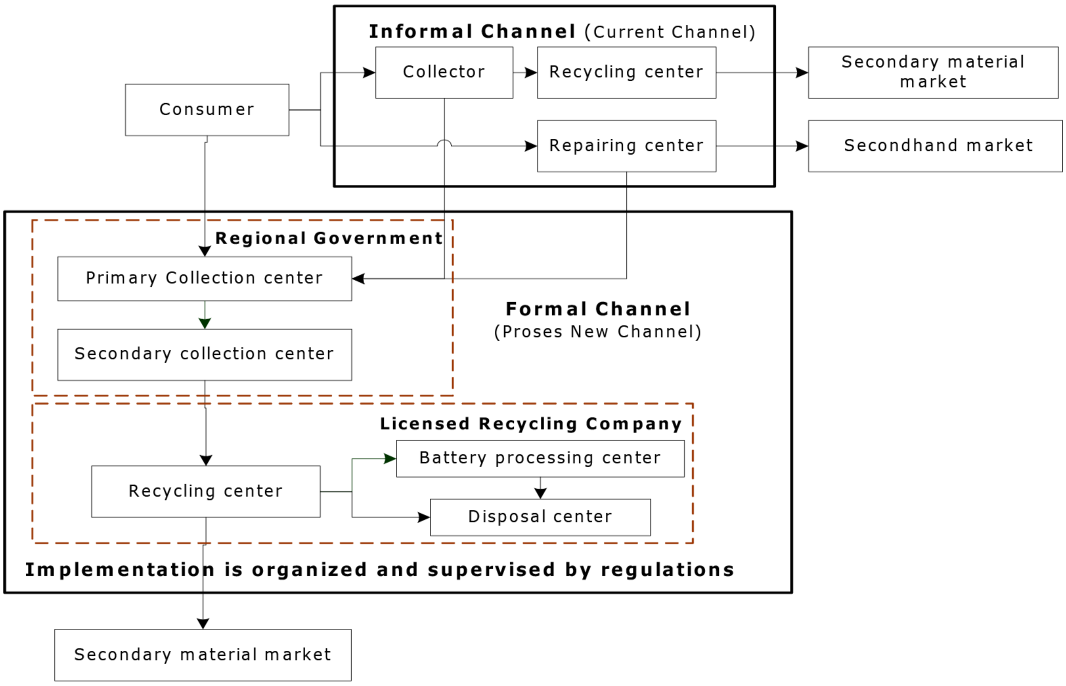

Figure 1. Developed Management Network Model

3.2. Mathematical Model

Before building a mathematical model, it is necessary to determine the notation used, which includes an index, decision variables and parameters.

3.2.1. Notations

Index:

t : index for time/period; $t = 1,2, \ldots, T$
p : index for used smartphone; $p = 1, 2, \ldots, P$
$q(Au)$: index for gold; $q(Au) = 1, 2, \ldots, Q(Au)$
$q(Ag)$: index for silver; $q(Ag) = 1, 2, \ldots, Q(Ag)$
$q(Pd)$: index for palladium; $q(Pd) = 1, 2, \ldots, Q(Pd)$
$q(Pt)$: index for platinum; $q(Pt) = 1, 2, \ldots, Q(Pt)$
$q(Ni)$: index for nickel; $q(Ni) = 1, 2, \ldots, Q(Ni)$
$q(Cu)$: index for copper; $q(Cu) = 1, 2, \ldots, Q(Cu)$
$q(Pb)$: index for lead; $q(Pb) = 1, 2, \ldots, Q(Pb)$
$q(Sn)$: index for tin; $q(Sn) = 1, 2, \ldots, Q(Sn)$
$q(Sb)$: index for antimony; $q(Sb) = 1, 2, \ldots, Q(Sb)$
u : index for consumer/user (CS); $u = 1, 2, \ldots, U$
i : index for repairing center (RpC); $i = 1, 2, \ldots, I$
h : index for secondhand market (SM); $h = 1, 2, \ldots, H$
$r(f)$: index for formal recycling center (FRC); $r(f) = 1, 2, \ldots, R(f)$
$r(i)$: index for informal recycling center (IRC); $r(i) = 1, 2, \ldots, R(i)$
s : index for secondary material market (SMM); $s = 1, 2, \ldots, S$
$c(i)$: index for informal collectors (IC); $c(i) = 1, 2, \ldots, C(i)$
$c(p)$: index for primary collection center (PCC); $c(p) = 1, 2, \ldots, C(p)$

$c(s)$: index for secondary collection center (SCC); $c(s) = 1, 2, \ldots, C(s)$
b : index for battery processing center (BPC); $b = 1, 2, \ldots, B$
x : index for disposal center (DsC); $x = 1, 2, \ldots, X$
q : index for secondary material; $q = 1, 2, \ldots, Q$
q^* : index for secondary material target; $q^* = 1, 2, \ldots, Q^*$

3.2.2. Decision Variables

Q_{puit} : The number of used smartphones (p) sold by CS (u) to RpC (i) during the time period (t)
Q_{piht} : The number of used smartphones (p) sent from RpC (i) to SM (h) during the time period (t)
$Q_{q(Au)r(i)st}$: Gold weight ($q(Au)$) sent from IRC ($r(i)$) to SMM (s) during the time period (t)
$Q_{q(Au)r(f)st}$: Gold weight ($q(Au)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Ag)r(f)st}$: Silver weight ($q(Ag)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Pd)r(f)st}$: Palladium weight ($q(Pd)$) sent from FRC ($r(f)$) to SMM(s) during the time period (t)
$Q_{q(Pt)r(f)st}$: Platinum weight ($q(Pt)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Ni)r(f)st}$: Nickel weight ($q(Ni)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Cu)r(f)st}$: Copper weight ($q(Cu)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Pb)r(f)st}$: Lead weight ($q(Pb)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Sn)r(f)st}$: Tin weight ($q(Sn)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{q(Sb)r(f)st}$: Antimony weight ($q(Sb)$) sent from FRC ($r(f)$) to SMM (s) during the time period (t)
$Q_{qr(f)xt}$: Residual material weight (q) sent from FRC ($r(f)$) to disposal center (x) during the time period (t)
Q_{qbxt} : Residual material weight (q) sent from BPC (b) to disposal center (x) during the time period (t)
$Q_{pc(p)c(s)t}$: The number of used smartphones (p) sent from PCC ($c(p)$) to SCC ($c(s)$) during the time period (t)
$Q_{pc(p)t}$: The total inventory of used smartphones (p) at PCC ($c(p)$) during the time period (t)
$Q_{pc(s)t}$: The number of used smartphones disassembled (p) at SCC ($c(s)$) during the time period (t)
$Q_{pc(s)t}$: The number of used smartphones sorted (p)at SCC ($c(s)$) during the time period (t)
$Q_{pr(f)bt}$: The number of used battery (p) sent from FRC ($r(f)$) to BPC (b) during the time period (t)
$Q_{pc(s)r(f)t}$: The number of used smartphones (p) sent from SCC ($c(s)$) to FRC ($r(f)$) during the time period (t)
$Q_{pc(s)t}$: The total inventory of used smartphones (p) at SCC ($c(s)$) during the time period (t)
$Q_{pr(f)t}$: The total inventory of used smartphones (p) at FRC ($r(f)$) during the time period (t)
$Q_{pr(i)t}$: The total inventory of used smartphones (p) at IRC ($r(i)$) during the time period (t)
Q_{pit} : The number of used smartphones (p) purchased by RpC (i) during the time period (t)
Q_{piht} : The number of used smartphones (p) repaired at RpC (i) during the time period (t) sold to SM (h)
$Q_{pic(p)t}$: The number of used smartphones (p) collected by RpC (i) to PCC ($c(p)$) during the time period (t)
$Q_{puc(p)t}$: The number of used smartphones (p) collected by CS (u) to PCC ($c(p)$) during the time period (t)
$Q_{puc(i)t}$: The number of used smartphones (p) discarded by CS (u) so it goes to IC ($c(i)$) during the time period (t)
$Q_{pc(i)c(p)t}$: The number of used smartphones (p) collected by IC ($c(i)$) to PCC ($c(p)$) during the time period (t)
$Q_{pc(i)r(i)t}$: The number of used smartphones (p) collected by IC ($c(i)$) to IRC ($r(i)$) during the time period (t)

3.2.3. Parameter

SP_{puit} : Selling price of product (p) from CS (u) to RpC (i) during the time period (t)
$I_{puc(p)t}$: Incentives received by CS (u) from collecting used products (p) to PCC ($c(p)$) during the time period (t)
$SP_{pc(i)r(i)t}$: Selling price of product (p) from IC ($c(i)$) to IRC (i) during the time period (t)

SP_{piht} : Selling price of product (p) from RpC (i) to SM (h) during the time period (t)
$I_{pic(p)t}$: Incentives received by RpC (i) from collecting used products (p) to PCC ($c(p)$) during the time period (t)
$I_{pc(i)c(p)t}$: Incentives received by IC ($c(i)$) from collecting used products (p) to PCC ($c(p)$) during the time period (t)
$SP_{q(Au)r(i)st}$: Selling price of gold ($q(Au)$) from IRC ($r(i)$) to SMM (s) during the time period (t)
$SP_{q(Au)r(f)st}$: Selling price of gold ($q(Au)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$Sp_{q(Ag)r(f)st}$: Selling price of silver ($q(Ag)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$Sp_{q(Pd)r(f)st}$: Selling price of palladium ($q(Pd)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$SP_{q(Pt)r(f.)st}$: Selling price of platinum ($q(Pt)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$SP_{q(Ni)r(f.)st}$: Selling price of nickel ($q(Ni)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$SP_{q(Cu)r(f.)st}$: Selling price of copper ($q(Cu)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$SP_{q(Pb)r(f.)st}$: Selling price of lead ($q(Pb)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$SP_{q(Sn)r(f.)st}$: Selling price of tin ($q(Sn)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$SP_{q(Sb)r(f.)st}$: Selling price of antimony ($q(Sb)$) from FRC ($r(f)$) to SMM (s) during the time period (t)
$TC_{pc(p)c(s)t}$: Transportation cost of product (p) from PCC ($c(p)$) to SCC ($c(s)$) during the time period (t)
$TC_{pc(s)bt}$: Transportation cost of product (p) from SCC ($c(s)$) to BPC (b) during the time period (t)
$TC_{pc(s)r(f.)t}$: Transportation cost of product (p) from SCC ($c(s)$) to FRC ($r(f)$) during the time period (t)
$TC_{qr(f.)xt}$: Transportation cost of materials (q) from FRC ($r(f)$) to DsC (x) during the time period (t)
$HC_{pc(p)t}$: Storage cost of used product (p) at PCC ($c(p)$) during the time period (t)
$HC_{pc(s)t}$: Storage cost of used product (p) at SCC ($c(s)$) during the time period (t)
$HC_{pr(f.)t}$: Storage cost of used product (p) at FRC ($r(f)$) during the time period (t)
$HC_{pr(i)t}$: Storage cost of used product (p) at IRC ($r(i)$) during the time period (t)
HC_{pit} : Storage cost of used product (p) at RpC (i) during the time period (t)
FC_i : Fixed costs at the RpC (i)
$FC_{c(p)}$: Fixed cost at PCC ($c(p)$)
$FC_{c(s)}$: Fixed cost at SCC ($c(s)$)
$FC_{r(f)}$: Fixed cost at FRC ($r(f)$)
$FC_{r(i)}$: Fixed costs at IRC ($r(i)$)
$DC_{pr(f.)t}$: Disassembly cost of product (p) at FRC ($r(f)$) during the time period (t)
$RC_{pr(f.)t}$: Recycling costs of products (p) at FRC ($r(f)$) during the time period (t)
$RC_{pr(i)t}$: Recycling costs of product (p) at IRC ($r(i)$) during the time period (t)
RC_{piht} : Repairing cost of used products (p) at RpC (i) during the time period (t) which is sold to SM (h)
$L_{c(p)c(s)}$: Distance between PCC ($c(p)$) and SCC ($c(s)$)
$L_{r(f)b}$: Distance between FRC ($r(f)$) and BPC (b)
$L_{c(s)r(f.)}$: Distance between SCC ($c(s)$) and FRC ($r(f)$)
$L_{r(f.)x}$: Distance between FRC ($r(f)$) and DsC (x)
L_{bx} : Distance between BPC (b) and DsC (x)
$a_{c(p)c(s)}$: Distance covered per litre of fuel for transportation from PCC ($c(p)$) to SCC ($c(s)$)
$a_{c(s)r(f.)}$: Distance covered per litre of fuel for transportation from SCC ($c(s)$) to FRC ($r(f)$)
$a_{r(f.)b}$: Distance covered per litre of fuel for transport from FRC ($r(f)$) to BPC (b)
$a_{r(f.)x}$: Distance covered per litre of fuel for transportation from FRC ($r(f)$) to DsC (x)
a_{bx} : Distance covered per litre of fuel for transportation from BPC (b) to DsC (x)
P_{bbm} : Fuel price per litre

β : Value of fuel emission per litre
$VC_{c(p)c(s)}$: Vehicle carrying capacity from PCC ($c(p)$) to SCC ($c(s)$)
$VC_{c(s)r(f.)}$: Vehicle carrying capacity from SCC ($c(s)$) to FRC ($r(f)$)
$VC_{r(f.)b}$: Vehicle carrying capacity from FRC ($r(f)$) to BPC (b)
$VC_{r(f.)x}$: Vehicle carrying capacity from FRC ($r(f)$) to DsC (x)
VC_{bx} : Vehicle carrying capacity from BPC (b) to DsC (x)
TRU : The total revenue CS (u)
$TRIC$: The total revenue RpC (i)
$TRR(i)C$: The total income IRC ($r(i)$)
$TRR(f)C$: The total income FRC ($r(f)$)
RU_i : CS (u) income from selling used products
$RU_{c(p)}$: Incentives received by CS (u) from collecting used products to PCC ($c(p)$)
$RU_{r(i)}$: Benefits received by CS (u) when distributing used products to IRC ($r(i)$)
$RR(i)_{Au}$: Revenue at at IRC ($r(i)$) from selling gold (Au)
$q(i)_{Au}*$: Target of gold (Au) generated per smartphone unit at IRC ($r(i)$)
$RR(f)_{Au}$: Revenue IRF ($r(f)$) from sales of gold (Au)
$q(f)_{Au}*$: Target of gold (Au) generated per smartphone unit at FRC ($r(f)$)
$RR(f)_{Ag}$: Revenue at FRC ($r(f)$) from sales of silver (Ag)
$q(f)_{Ag}*$: Target of silver (Ag) generated per smartphone unit at FRC ($r(f)$)
$RR(f)_{Pd}$: Revenue at FRC ($r(f)$) from sales of palladium (Pd)
$q(f)_{Pd}*$: Target of palladium (Pd) produced per smartphone unit at FRC ($r(f)$)
$RR(f)_{Pt}$: Revenue at FRC ($r(f)$) from platinum sales (Pt)
$q(f)_{Pt}*$: Target of platinum (Pt) generated per smartphone unit at FRC ($r(f)$)
$RR(f)_{Cu}$: Revenue at FRC ($r(f)$) from sales of copper (Cu)
$q(f)_{Cu}*$: Target of copper (Cu) produced per smartphone unit at FRC ($r(f)$)
$RR(f)_{Ni}$: Revenue at FRC ($r(f)$) from nickel (Ni) sales
$q(f)_{Ni}*$: Target of nickel (Ni) produced per smartphone unit at FRC ($r(f)$)
$RR(f)_{Pb}$: Revenue at FRC ($r(f)$) from sales of lead (Pb)
$q(f)_{Pb}*$: Target lead (Pb) generated per smartphone unit in FRC ($r(f)$)
$RR(f)_{Sn}$: Revenue at FRC ($r(f)$) from sales of tin (Sn)
$q(f)_{Sn}*$: Target of lead (Sn) produced per smartphone unit at FRC ($r(f)$)
$RR(f)_{Sb}$: Revenue at FRC ($r(f)$) from sales of antimony (Sb)
$q(f)_{Sb}*$: Target of antimony (Sb) produced per smartphone unit at FRC ($r(f)$)
$TTCC(p)C(s)$: The total transportation costs from PCC ($c(p)$) to SCC ($c(s)$)
$TTCC(s)B$: The total transportation costs from SCC ($c(s)$) to BPC (b)
$TTCC(s)R(f)$: The total transportation costs from SCC ($c(s)$) to FRC ($r(f)$)
$TTCR(f)X$: The total transportation costs from FRC ($r(f)$) to DsC (x)
$THCCp$: The total cost of storage at PCC ($c(p)$)
$THCCs$: The total cost of storage at SCC ($c(s)$)
$THCR(f)$: The total cost of storage at FRC ($r(f)$)
$THCR(i)$: The total cost of storing at IRC ($r(i)$)
$THCI$: The total cost of storage at RpC (i)

TFCC(p) : The total fixed costs at PCC (*c*(*p*))
TFCC(s) : The total fixed costs at SCC (*c*(*s*))
TFCR(f) : The total fixed costs at FRC (*r*(*f*))
TFCR(i) : The total fixed costs at IRC (*r*(*i*))
TFCI : The total fixed costs at RpC (*i*)
TICC(p) : The total cost for incentives at PCC (*c*(*p*))
TDCR(f) : The total disassembly costs at FRC (*r*(*f*))
TSCR(f) : The total cost of sorting at FRC (*r*(*f*))
TRCR(i) : The total recycling costs at IRC (*r*(*i*))
TRCR(f) : The total recycling costs at FRC (*r*(*f*))
TPCI : The total purchase cost at RpC (*i*)
TRCI : The total cost of repairs at RpC (*i*)
TECF : Environmental impacts of transportation activities due to the use of diesel fuel
TECR(f) : The total environmental impact at FRC (*r*(*f*))
$ERC_{pr(f)t}$: Environmental costs of recycling used products (*p*) at FRC (*r*(*f*)) during the time period (*t*)
TECR(i) : The total environmental impact at IRC (*r*(*i*))
$ERC_{pr(i)t}$: Environmental costs of recycling used products (*p*) at IRC (*r*(*i*)) during the time period (*t*)
TCVM : The total cost of virgin mining

The flow of input and output as well as material which is the decision variable of each center is shown in figure 2 below.

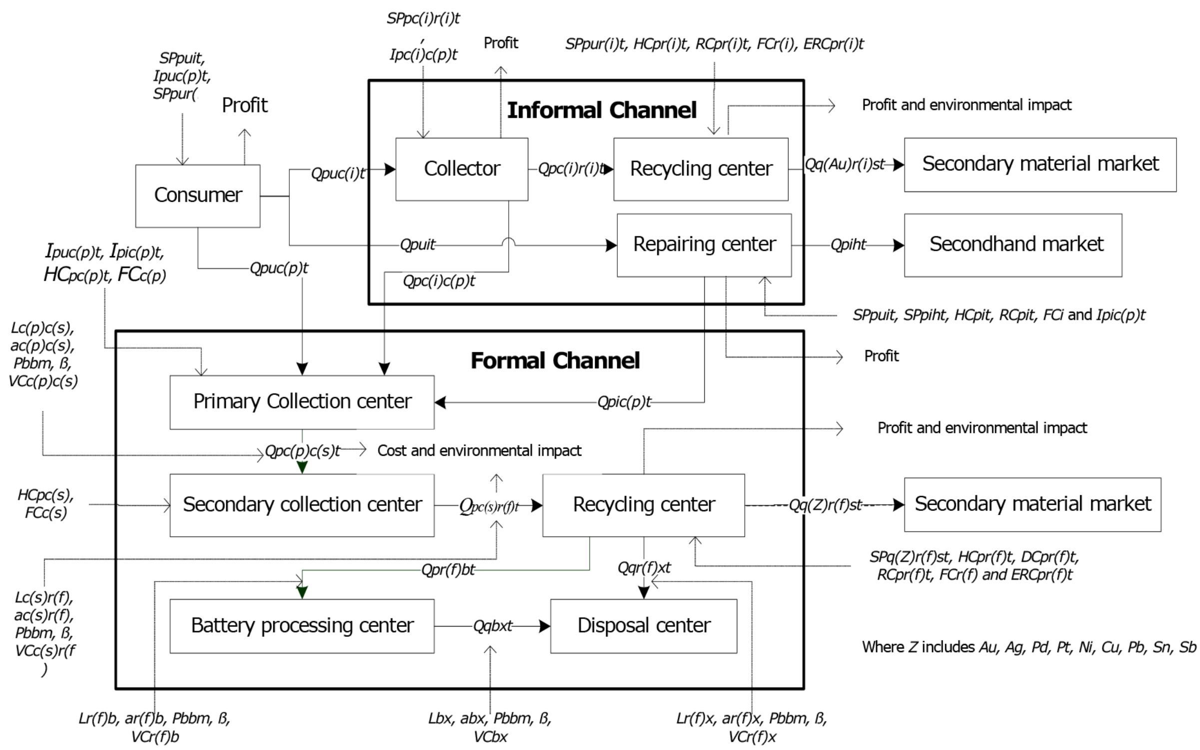

Figure 2. Input and Output of Each Center

3.2.4. Components of Revenue and Cost

The profit component includes all RL management centers' revenue and total costs, including transportation, environmental impact, and virgin mining costs. Income components are obtained from consumers, informal channels, and formal channels. Income from the consumer side is obtained from product sales to repair centers, incentives received for collecting smartphone waste to a collection center, and secondhand product sales by repairing center. Meanwhile, for the formal channel, revenue is derived from the sale of secondary materials from the recycling center, including gold, silver, palladium, platinum, nickel, copper, lead, tin, and antimony.

Total revenue from consumers/users accumulate product sales to repairing centers and incentives for collecting them to PCC. The total income for informal collectors is obtained from selling smartphone waste to informal recycling centers or receiving incentives from collection to primary collection centers. The informal collector will choose the one that provides the higher compensation. The repairing center total revenue is obtained from the sale of secondhand products that have been repaired and the incentives that will be received if they collect to PCC for products that are not sold. The metal product produced from informal recycling is gold, so the income for the informal recycling center is obtained from the sale of gold. Metal products produced from formal recycling are more varied than from informal recycling. The formal recycling process produces secondary materials such as gold, silver, platinum, palladium, nickel, copper, lead, tin, and antimony.

The total cost of smartphone waste management includes costs at repair centers, informal recycling centers, primary collection centers, secondary collection centers, formal recycling centers, and transportation costs. The total cost at the repair center consists of purchase, repair, storage, and fixed costs. The components that makeup costs in informal recycling centers include purchase, recycling, storage, and fixed costs. The total cost at the primary collection center consists of incentive fees for consumers, informal collectors, and repairing centers that collect smartphone waste to PCC, storage costs, and fixed costs to SCC. The components that make up the secondary collection center costs include storage costs and fixed costs. The components that make up the costs at a formal recycling center include disassembly, recycling, storage, and fixed costs. Total transportation costs are the accumulated transportation costs from the primary collection center (PCC) to the secondary collection center, from the secondary collection center (SCC) to the formal recycling center, from the formal recycling center to the battery processing center and finally from the formal recycling center and battery processing center to disposal center. Transportation costs for collection from the user/repairing center to the primary collection center and sales to the repairing center or informal recycling center are not considered in the model built because each carries them out. Transportation costs for collection from users/repairing centers/informal collectors to primary collection centers and sales to repairing centers and informal recycling centers are not considered in the model built because they are carried out by each/independent.

3.2.5. Component of Environmental Impact Cost Components

Environmental impact costs include the costs of environmental impacts from recycling activities on the informal and formal channel and the costs of environmental impacts arising from transportation activities for the formal channel. To determine the cost of the environmental impact of recycling activities, both informal and formal, use a life cycle assessment with the eco-cost method. Meanwhile, for the environmental impact of transportation activities, the Environmental Priority Strategy (EPS) with the Environmental Load Unit (ELU) scale is used; the price for each ELU is one EUR. The main principle of EPS is to assign emissions to an impact category when an actual effect has occurred or is likely to occur in the environment. In this model, the subject of environmental impacts from transportation activities is the impact of the use of vehicle fuel which is focused on transportation activities where the value to be paid is the exhaust gas emissions generated from the vehicles used for transportation. Using the EPS method to measure the environmental impact of transportation activities is that when fossil fuels and greenhouse gas emissions are relatively high, the EPS method shows a more significant environmental impact than other methods (Mattsson, 2012).

3.2.6. Virgin Mining Cost

Virgin mining or mining materials from nature costs seven times higher than processing smartphone waste for the same volume and variant of metal materials. Informal recycling is not considered in these cost savings because the product volume is far below that of formal recycling. So, suppose recycling is carried out through informal or reused channels (secondhand market). In that case, virgin mining cost seven times (7x) the cost of formal recycling multiplied by the number of recycled and reused smartphones (Zeng, Mathews & Li, 2018).

3.2.7. Mathematical Model

The objective function of the mathematical model built is the maximization of profit received along the management path. That is obtained from the total income minus the total cost and the total cost of environmental impact plus the savings obtained from refining materials from natural mining (virgin mining). Profit is earned from revenue at the repairing center + income at the informal recycling center + income at the formal recycling center – total cost at the repairing center – total cost at the informal recycling center – total cost at the primary collection center – total cost at the secondary collection center – total cost to the formal recycling center – total cost of the battery processing center – total cost of the environmental impact from activities at the informal recycling centers – total cost of the environmental impact of inter-center transportation activities – total cost of the environmental impact from activities at the formal recycling center + virgin mining total cost, as shown in equation (1) and (2)

Constraints that must be met in the designed reverse logistics network includes:

a) The product purchased by the repairing center is a product that is still suitable for use or still in the product lifetime
b) The products sold by the repairing center to the secondhand market do not exceed the demand for secondhand products
c) Products sent to the primary collection center do not exceed the supply of used products from consumers minus the products sold in the secondhand market
d) The number of products sent to the primary collection center and sold at the repairing center does not exceed the supply of used products from consumers.
e) The product sent to the secondary collection center does not exceed the product received to the primary collection center
f) The number of products stored in each center over a period of time does not exceed the center's storage capacity
g) The number of products repaired at the repairing center does not exceed the repair capacity at the repairing center
h) The number of products sorted/unloaded at the recycling center does not exceed the capacity of sorting/unloading at the recycling center
i) The number of products recycled at the recycling center must not exceed the recycling capacity of the recycling center
j) The number of products/materials sent must not exceed the capacity of the destination center
k) The target weight of secondary material produced by the formal recycling center from 1 ton of smartphone waste (1 ton of smartphone waste contains approximately 8000 smartphones) is 347 gr of gold, 3,630 gr of silver, 151 gr of palladium, 5 gr of platinum, 15,000 gr of nickel, 128,000 gr of copper, 6,000 gr of lead, 10,000 gr of lead, and 1,000 gr of antimony (Navazo, Méndez & Peiró, 2014).
l) The target weight of gold produced by the informal recycling center is 158.8 gr from 1 ton of smartphone waste.
m) The number of products entering the primary collection center is the same as those entering the secondary collection center, recycling center, and battery recycling center
n) The number of used smartphones sold by consumers is the same as the number of products at the repairing center
o) The repairing center will collect unsold products to the primary collection center
p) The number of products that enter the primary collection center is the accumulation of products from consumers, informal collectors, and repairing centers
q) The number of products that are discarded and enter informal collectors is the rest of the products that do not enter the primary collection center and repairing center
r) Non-negativity constraint
s) All decision variables other than secondary material are integer values

The objective function of the built model is shown in Equations (1) and (2), while the constraint function is shown in Equations (3) to (35).

Objective Function

$$\begin{aligned}\text{Max } Z = {} & \{TRU + TRIC + TRR(i)C + TRR(f)C\} - \{(TPCI + TRCI + TICI + TFCI) + (TRCR(i) \\ & + THCR(i) + TFCR(i)) + (TICC(p) + THCC(p) + TTCC(p)C(s) + TFCC(p)) + (TDCC(s) \\ & + TSCC(s) + TTCC(s)B + TTCC(s)R(f) + THCC(s) + TFCC(s)) + (TRCR(f) + TTCR(f)X \\ & + THCR(f) + TFCR(f))\} - \{TECR(f) + TECR(i) + TECF\} + TCVM\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Max } Z = {} & \Sigma_p\Sigma_u\Sigma_i\Sigma_t (Q_{puit} \times R_{puit}) + \Sigma_p\Sigma_u\Sigma_{c(p)}\Sigma_t (Q_{puc(p)t} \times I_{puc(p)t}) + \Sigma_p\Sigma_i\Sigma_b\Sigma_t(Q_{pibt} \times R_{pibt}) \\ & + \Sigma_{q(Au)}\Sigma_{r(i)}\Sigma_s\Sigma_t (Q_{q(Au)r(i)st} \times SP_{q(Au)r(i)st}) + \Sigma_{q(Au)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Au)r(f)st} \times SP_{q(Au)r(f)st}) \\ & + \Sigma_{q(Ag)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Ag)r(f)st} \times SP_{q(Ag)r(f)st}) + \Sigma_{q(Pd)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Pd)r(f)st} \times SP_{q(Pd)r(f)st}) \\ & + \Sigma_{q(Pt)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Pt)r(f)st} \times SP_{q(Pt)r(f)st}) + \Sigma_{q(Ni)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Ni)r(f)st} \times SP_{q(Ni)r(f)st}) \\ & + \Sigma_{q(Cu)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Cu)r(f)st} \times SP_{q(Cu)r(f)st}) + \Sigma_{q(Pb)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Pb)r(f)st} \times SP_{q(Pb)r(f)st}) \\ & + \Sigma_{q(Sn)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Sn)r(f)st} \times SP_{q(Sn)r(f)st}) + \Sigma_{q(Sb)}\Sigma_{r(f)}\Sigma_s\Sigma_t (Q_{q(Sb)r(f)st} \times SP_{q(Sb)r(f)st}) \\ & - \Sigma_p\Sigma_u\Sigma_i\Sigma_t (Q_{puit} \times PC_{puit}) - \Sigma_p\Sigma_i\Sigma_b\Sigma_t (Q_{pibt} \times RC_{pibt}) - \Sigma_p\Sigma_i\Sigma_t (Q_{pit} \times HC_{pit}) \\ & - \Sigma_i FC_i - \Sigma_p\Sigma_{r(i)}\Sigma_t (Q_{pr(i)t} \times RC_{qr(i)t}) - \Sigma_p\Sigma_{r(i)}\Sigma_t (Q_{pr(i)t} \times HC_{qr(i)t}) - \Sigma_{r(i)} FC_{r(i)} \\ & - \Sigma_p\Sigma_u\Sigma_{c(p)}\Sigma_t (Q_{puc(p)t} \times I_{puc(p)t}) - \Sigma_p\Sigma_{c(p)}\Sigma_t (Q_{pc(p)t} \times HC_{pc(p)t}) - \Sigma_p\Sigma_{c(p)}\Sigma_{c(s)}\Sigma_t (Q_{pc(p)c(s)t} \times TC_{pc(p)c(s)t}) \\ & - \Sigma_{c(p)} FC_{c(p)} - \Sigma_p\Sigma_{c(s)}\Sigma_t (Q_{pc(s)t} \times DC_{pc(s)t}) - \Sigma_p\Sigma_{c(s)}\Sigma_t (Q_{pc(s)t} \times SC_{pc(s)t}) \\ & - \Sigma_p\Sigma_{c(s)}\Sigma_b\Sigma_t (Q_{pc(s)bt} \times TC_{pc(s)bt})\ \Sigma_p\Sigma_{c(s)}\Sigma_{r(f)}\Sigma_t (Q_{pc(s)r(f)t} \times TC_{pc(s)r(f)t}) - \Sigma_p\Sigma_{c(s)}\Sigma_t (Q_{pc(s)t} \times HC_{pc(s)t}) \\ & - \Sigma_{c(s)} FC_{c(s)} - \Sigma_p\Sigma_{r(f)}\Sigma_t (Q_{pr(f)t} \times RC_{pr(f)t}) - \Sigma_p\Sigma_{r(f)}\Sigma_x\Sigma_t (Q_{pr(f)xt} \times TC_{pr(f)xt}) \\ & - \Sigma_p\Sigma_{r(f)}\Sigma_t (Q_{pr(f)t} \times HC_{pr(f)t}) - \Sigma_{r(f)} FC_{r(f)} - \Sigma_p\Sigma_{r(i)}\Sigma_t (Q_{pr(i)t} \times ERC_{pr(i)t}) \\ & - \Sigma_p\Sigma_{r(f)}\Sigma_t (Q_{pr(f)t} \times ERC_{pr(f)t}) - 2\beta/\alpha\{[(\Sigma_{c(p)}\Sigma_{c(s)} (Q_{pc(p)c(s)t} \times L_{c(p)c(s)}))/VC] \\ & + [(\Sigma_{c(s)}\Sigma_b (Q_{pc(s)bt} \times L_{c(s)b}))/VC] + [(\Sigma_{c(s)}\Sigma_{r(f)} (Q_{pc(s)r(f)t} \times L_{c(s)r(f)}))/VC] \\ & + [(\Sigma_{r(f)}\Sigma_x (Q_{pr(f)xt} \times L_{r(f)x}))/VC]\} + 7 \times \Sigma_p\Sigma_i\Sigma_b\Sigma_{r(f)} \Sigma_t \{(Q_{pibt} + Q_{pr(f)t}) \times RC_{pr(f)t}\}\end{aligned} \tag{2}$$

Subject to:

$$Q_{pit} \leq (1\text{-average lifetime/lifetime}) \times S \tag{3}$$

$$Q_{pit} \leq 0.44 \times S \tag{4}$$

$$Q_{pibt} \leq Q_{pit} \tag{5}$$

$$Q_{pc(p)t} \leq S - Q_{pibt} \tag{6}$$

$$Q_{pc(p)t} + Q_{pit} \leq S \tag{7}$$

$$Q_{pc(p)c(s)\ t} \leq Q_{pc(p)t} \tag{8}$$

$$Q_{pit} \leq HCI \tag{9}$$

$$Q_{pit} \leq RCI \tag{10}$$

$$Q_{pc(p)t} \leq HCCp \tag{11}$$

$$Q_{pc(s)t} \leq SCCs \tag{12}$$

$$Q_{prt} \leq HCR \tag{13}$$

$$Q_{prt} \leq RCR \tag{14}$$

$$Q_{pc(s)t} \leq DCCs \tag{15}$$

$$Q_{qrst} \leq CS \tag{16}$$

$$Q_{qrst} \leq CX \tag{17}$$

$$Q_{pc(s)bt} \leq CB \tag{18}$$

$$Q_{q(Au)r(f)st} \leq q(f)_{Au}^{*} \times Q_{pr(f)t} \tag{19}$$

$$Q_{q(Ag)r(f)st} \leq q(f)_{Ag}^{*} \times Q_{pr(f)t} \tag{20}$$

$$Q_{q(Pd)r(f)st} \leq q(f)_{Pd}^{*} \times Q_{pr(f)t} \tag{21}$$

$$Q_{q(Pt)r(f)st} \leq q(f)_{Pt}^{*} \times Q_{pr(f)t} \tag{22}$$

$$Q_{q(Ni)r(f)st} \leq q(f)_{Ni}^{*} \times Q_{pr(f)t} \tag{23}$$

$$Q_{q(Cu)r(f)st} \leq q(f)_{Cu}^{*} \times Q_{pr(f)t} \tag{24}$$

$$Q_{q(Pb)r(f)st} \leq q(f)_{Pb}^{*} \times Q_{pr(f)t} \tag{25}$$

$$Q_{q(Sn)r(f)st} \leq q(f)_{Sn}^{*} \times Q_{pr(f)t} \tag{26}$$

$$Q_{q(Sb)r(f)st} \leq q(f)_{Sb}^{*} \times Q_{pr(f)t} \tag{27}$$

$$Q_{q(Au)r(i)st} \leq q(f)_{Au}^{*} \times Q_{pr(i)t} \tag{28}$$

$$Q_{pc(p)t} = Q_{pc(s)t} = Q_{pc(p)c(s)t} = Q_{pc(s)r(f)t} = Q_{pr(f)t} = Q_{pc(s)bt} \tag{29}$$

$$Q_{puit} = Q_{pit} \tag{30}$$

$$Q_{pic(p)t} = Q_{puit} - Q_{piht} \tag{31}$$

$$Q_{pc(p)t} = Q_{puc(p)t} + Q_{pic(p)t} + Q_{pc(i)c(p)t} \tag{32}$$

$$Q_{puc(i)t} = S - Q_{puc(p)t} + Q_{puit} \tag{33}$$

$$Q_{puit}, Q_{puc(i)t}, Q_{pup(c)t}, \ldots, Q_{pihtt}, Q_{qrst} \geq 0 \tag{34}$$

All decision variables other than Q_{qrst} are integer values (35)

4. Result and Discussion

4.1. Management Network

Based on Figure 1, consumers are suppliers of smartphone waste. Consumers can sell in the secondhand market if the smartphone still functions correctly. If the smartphone is no longer functioning correctly, then consumers can distribute smartphone waste on formal or informal channels. Formal channels are much more environmentally friendly and more profitable than informal channels. When smartphone waste is disposed of, it will be picked up by informal collectors and goes into the recycling process by unauthorized informal actors. Meanwhile, a licensed company will carry out the recycling process for the formal channel. Consumers can collect smartphone waste at PCC provided in several sub-districts when choosing the formal channel. Smartphone waste is then transported from PCC and then collected to SCC. Then the smartphone waste will be transported to a licensed waste treatment company.

4.1.1. Consumers as Suppliers of Used Products

Consumers are suppliers of smartphone waste. The total population of Yogyakarta in 2020 is 3,668,729 people or 1.4% of the total population of Indonesia if the total population of Indonesia is 270.2 million people (Central Bureau of Statistics, 2021). If 63.53% are smartphone users (Nurhayati-Wolff, 2020), then smartphone users in Yogyakarta are 2,330,744 people. Based on the survey results, Indonesians' average smartphone lifespan is 1.9 years. This number is strengthened by previous research, which shows that the average lifespan of Indonesians is 1.5 to 2 years (Ulya, 2019; Zaenudin, 2017). If one smartphone weighs 165.43 gr (Guvendik, 2014), including the battery, then with an average lifetime of 1.9 years per year, it will produce 202,934,159 kg of waste or 203 tons. The average monthly supply of used smartphones is 101,377 units or 16,764,126.2 gr or 16,764.126 kg. According to the

Consumer Technology Association survey in 2014, the average age of a smartphone is 4.7 years (ComputerCare, 2019). Generally, the age of using electronic products can last up to 5 years. The service life is shorter than the product life; consumers will most likely replace their smartphone not because it is damaged but because they are bored or curious about other products. This condition allows used products still functioning well to be resold in the used goods market. Products that are no longer working are collected at PCC. Consumers can sell used products if they are still functioning correctly; if the smartphone is not working, the consumer can collect it at the PCC. In addition, some consumers may dispose of their e-waste, which will be collected by informal collectors and sent to informal recycling. Based on the results of the distribution of consumer behavior questionnaires, out of 334 respondents, 244 respondents stated that they were willing to take their waste to the PCC provided by the government if they were given incentives in the form of cash or discounts on the purchase of new products. The remaining 90 people, or 26.94%, do not want incentives when bringing the electronic waste to PCC.

4.1.2. Informal Channel

Smartphone waste management can be done through informal or formal channels. For informal channels, two centers play a role, namely repairing and recycling centers.

1. Repairing Center

   Repairing centers are centers of the secondhand and repair market, while informal recycling centers focus on recycling. Based on a survey conducted on 325 respondents, 143 are consumers of the secondhand market, so the potential for the secondhand market is still quite enormous, which is 44% (Sari, Masruroh & Asih, 2021c). The average cost of buying a used smartphone from a consumer is 1×10^6 IDR. The average cost for reconditioning a smartphone is 2.10 USD (Geyer & Blass, 2010) or 29,892.45 IDR. The difference between the selling price and the phone's purchase price is 17 USD (Geyer & Blass, 2010) or 241,986.50 IDR, so the selling price of the product to the secondhand market is 1,241,986.50 IDR. Storage costs of 40% of average earnings due to risk of technology obsolescence etc. In Yogyakarta Province, there are five regencies/cities, assuming there are 50 outlets per regency/city with fixed costs for outlet rental and employee salaries is 5×10^6 IDR per month, the total fixed cost for one month is 1.25×10^9 IDR.

2. Informal Recycling Center

   Individuals carry out informal recycling activities; due to a lack of knowledge and facilities, this practice pays less attention to health and environmental aspects. Using the eco-cost method, the cost of the environmental impact is enormous, namely 3.188×10^8 EUR (Sari, Masruroh, & Asih, 2023) or equivalent to 5.149×10^{12} IDR for 8,000 units, so that per-unit costs 6.436×10^8 IDR. One ton of smartphone waste produces 158.8 gr of gold; if the gold price is 832,008.38 IDR per gr, it will generate an income of 132,122,930.74 IDR or equivalent to 16,515,366 IDR per unit of smartphone waste. The production cost per ton is 13,046,510 IDR, and then per unit, it is 1,630.81 IDR. Burning electronic waste using coal. The energy produced from coal is 24.8 MJ/kg of Energy (Malaidji, Anshariah & Budiman, 2018), so to produce 6960 MJ of energy, it takes 320.968 kg of coal for 61.63 USD/ton per October 2021 (Kementarian Energi dan Sumber Daya Mineral, n.d.). The price of nitric acid per 37,000 gr is 490,000 IDR (Tokopedia (n.d.a). Meanwhile, the price of hydrochloric acid is 22,500 IDR/1200 gr (Tokopedia (n.d.b). So, the income obtained is 16,515.37 IDR per unit of smartphone waste, with a production cost of 1,630.81 IDR per unit. Informal recyclers buy used smartphones from informal collectors for 7,000 IDR per PCB. The fixed costs for informal recycling centers could be better because the equipment is relatively simple. Fixed costs per month are estimated at 2.5×10^6 IDR.

4.1.3. Formal Channel

The formal channel starts with smartphone waste collection activities at the primary collection center, then transported to the secondary collection center as a temporary shelter before being transported further to the formal recycling and battery processing center and finally transporting the remaining recycled waste to the disposal center. So apart from having activities in the center, there are also transportation activities.

1. Primary Collection Center (PCC)

   Based on the calculation results for determining the primary collection center (Sari, Masruroh & Asih, 2021d), as many as 30 PCCs must be built. This facility serves as a collection center to provide convenience to consumers. Based on the total Dropbox needs calculation results, it requires 93 drop boxes. The dropbox number of PCCs varies depending on each PCC supply; it is hoped that all supplies can be accommodated in the dropbox. If the price per dropbox is 2.5×10^6 IDR with a service life of 5 years and the number of dropboxes is 93 units, the total cost is 2.325×10^8 IDR, so the fixed monthly cost is 3.875×10^6 IDR. PCC has no storage cost because it does not require a storage process and the risk of damage. Where incentives are required for consumers to collect, incentives for consumers will be issued at the PCC. The incentives given should be higher than the selling price of waste in informal channels to attract consumers or informal collectors willing to participate in collecting at collection centers provided by the Government. If the informal recycling center compensation 7,000 IDR/unit, then the incentive is given at PCC at least 10,000 IDR per unit.

2. Secondary Collection Center

   The area of Yogyakarta Province is not that large compared to other provinces in Indonesia, which is only 3,186 km², so it only requires one SCC facility as a temporary shelter for all PCCs in the province before being sent to a recycling center for transportation efficiency. Waste transportation from PCC to SCC can be done independently by the Regional Government (Department of Environment and Forestry of Yogyakarta Province). A licensed company must do transportation from SCC to the recycling center for transportation from SCC to the recycling center. This practice refers to Government Regulation (PP) No. 27 of 2020. Specific household waste management is then collected in dropboxes or temporary storage and transported to SCC; transportation does not have to be carried out by a licensed company. Meanwhile, a licensed company must carry out transportation from SCC; this refers to PP No.22 of 2021 concerning the implementation of environmental protection and management. Activities in SCC are temporary storage. Therefore, temporary storage is also carried out at this facility, costing 200 IDR per unit. The construction cost of this temporary shelter facility is estimated to be 1×10^8 IDR with a life time of 5 years, so the fixed cost per month is 1.667×10^6 IDR .

3. Formal Recycling Center

   There are several formal recycling center facilities, but most are still limited to the incineration process. The results of incineration that are already hazardous and toxic materials (B3)-free are disposed of in the landfills of each waste processing company, such as those carried out by PT Arah Environmental Indonesia, PT. Internusa Environmental Teknotama, PT Prasadha Pamunah Industrial Waste etc. Now, in Indonesia, companies need to be more capable of recycling smartphone PCBs into secondary materials.

   PT Prasadha Pamunah Limbah Industri (PPLI) is an Indonesian company operating since 1994 providing metal recycling services. The result of collaboration between the Government (the Ministry of Environment and Forestry) with PT. Dowa. At PT. PPLI, the smartphone is disassembled manually. The battery can no longer be used, so it must be discarded. However, before that, these components must receive special treatment by immersing them in a specific liquid for 3-5 days to remove their electrical charge. They were then sliced into two parts, mixed in a mortar, and shaped like a brick. These batteries are then disposed of in landfills, while the plastic parts of smartphones are collected and then crushed using a granulator tool. The chopped results will come out in the form of plastic ores. This plastic ore is sold to third parties for recycling. The last most valuable component is the circuit board or PCB. This circuit board was sent to the parent company PT PPLI in Japan for processing in Dowa Eco-System Co Ltd. Dowa has a long experience in environmental management and recycling, Dowa has the technology to process electronic waste to sort out precious metals, such as gold, silver, tin, and copper (Syahban, 2018b). One of the problems in this industry is the lack of raw material supply. If the supply of raw materials is sufficient, PT PPLI may recycle PCBs in Indonesia.

One of the recycling techniques is pyrometallurgical processes. In the pyrometallurgical process, raw materials are heated and melted in a furnace at 1,500 °C. Besides pyrometallurgical, there is hydrometallurgical. The pyrometallurgical requires advanced technology for process optimization and extensive infrastructure such as integrated smelting and is only economically feasible on a large scale. That is an important difference between pyrometallurgical and hydrometallurgical processes. The infrastructure for this process requires a large economic investment. After smelting, the following treatment can be continued pyrometallurgical in the furnace anode-converter-electrolyte refining line. And then conversion, flame purification, the casting of anodes in anode furnaces, and electrolytic refining (Navazo et al., 2014). One ton of smartphones produces 147 kg of black copper, 17 kg of tin bars, and 396 kg of slag. The black copper fraction contains 128 kg of copper, 15 kg of nickel, 3.63 kg of silver, 347 gr of gold, 151 gr of palladium, and 5 gr of platinum. Tin bars contain 6 kg of lead, 10 kg of tin, and 1 kg of antimony. The total slag collected was 396 kg, with the main components silica (116 kg, derived from PWB plastic), iron (65 kg), and aluminium oxide (47 kg) (Navazo et al., 2014). The investment cost of the Umicore recovery facility in Hoboken requires an investment of more than 1 Billion USD (Hageluken, 2006) with a capacity of 350,000 tons per year; the investment cost of equipment and buildings for a recycling facility in developed countries is 700,000 USD (Zeng et al., 2018). The age of the machine can be up to 25 years (Antam, 2015). If the procurement cost is 1 Billion USD, it is equals 1.423×10^{13} IDR. A supply of 101,336 units or 12.67 tons can be completed in a day. The fixed cost per day is 1.582×10^{9} IDR. Operating costs are 1,490.85 USD per ton (Zeng et al., 2018), 1,490.85 USD for 1 ton of smartphones; if 1 ton contains 8000 smartphones, then the cost for one smartphone is 0.186 USD. The average 2006 cost of extracting precious metals for the US smartphone recycling company ECS Refining was 0.18 USD (Blass, Fuji, Neira, Favret, Mahdavi, Miller et al., 2006), these two sources give almost the same value. Recycling costs per ton of battery are 1,000 USD to 2,000 USD (Battery University, 2021). If the cost of recycling the battery per ton uses the highest value of 2,000 USD and the weight per battery is 38.6 gr, then the cost of recycling per battery is 1098.90 IDR. Before the recycling process, the battery is disassembled from the smartphone. The cost of dismantling is 200 IDR/unit. The cost of virgin mining or primary metal production costs seven times the cost of PCB recycling (Zeng et al., 2018).

The total revenue from recycling 1 ton of smartphones is 5.031×10^{8} IDR. If 1 ton contains 8,000 smartphones, the income per smartphone from recycling activities is 62,885.92 IDR. Therefore, the environmental impact cost for 1 ton of smartphones is -3.12×10^{9} EUR (Sari et al., 2023). Due to the negative value, no costs are incurred to address the environmental impacts of this practice, so the environmental impact costs are considered to be zero. Suppose the chosen location for the formal recycling center is PT. PPLI, the distance from SCC to the recycling center is 578.9 km.

4. Transportation Process

Every month there will be transportation from PCC to SCC. The truck used for transportation is a closed garbage truck with a 4-5 tons capacity. There are four transportation routes for waste supply per month by considering the amount of supply, vehicle capacity, and vehicle operator working hours. The costs incurred in the transportation process from CPP to SCC are transportation costs and environmental impact costs from transportation activities. Transportation costs are based on fuel consumption. The total distance traveled from the four routes is 572.8 km; if the fuel consumption is 5 km/litre and the fuel price is 11,150 IDR, then the total cost of transportation is 1,277,344 IDR per month. Meanwhile, the environmental impact costs of this transportation activity follow a variable magnitude depending on the cargo carried from each route sequence.

Transporting smartphone and battery waste to recycling centers uses vehicles from waste processing companies, using vehicles with a capacity of 10 tons and fuel consumption of 3 km/litre. The costs incurred in the transportation process from PCC to SCC are transportation costs and environmental impact costs from transportation activities. Transportation costs are based on fuel consumption. The number of trips is rounded up, with a capacity of 10 tons; as an illustration, if the smartphone waste that must be carried is 8 tons, then the number of transportation trips is one time of transportation instead of 0.8 times.

Calculating the environmental impact of transportation activities begins with identifying the composition of the fuel used by the transport vehicle. Transport vehicles use diesel fuel. The vehicles used for transportation are double six tire trucks (Jakarta Smart City, n.d.) with a capacity of 12m^3 or 5 tons (Ministry of Public Works, 2005) for transportation from PCC to SCC and tronton trucks for transportation from SCC to the recycling center. With a capacity of 10 to 12 tons. The composition of 1 kg of Diesel Fuel includes 0.865 kg of carbon (*C*), 0.013 of sulphur (*S*), 2×10^{-8} kg of mercury (*Hg*) and 1.1×10^{-7} of lead (*Pb*) (Indrianti & Rustikasari, 2010). One litre of diesel fuel weighs 0.85 kg, so diesel density is 0.85 kg/lt (Firdaus & Santoso, 2020). Table 2 shows the emission index and compound value in ELU. The emissions produced by 1 kg of diesel fuel and 1 litre of diesel fuel and air emissions index generated per 1 kg of diesel fuel converted to each litre of fuel. The air emission index indicates the category of the default method of EPS 2000, which was later used to get the emission value in ELU. One EUR is 16,152.33 IDR (KursDollar, n.d.). The value of exhaust gas emissions of diesel fuel into the air in the EPS defaults method is obtained by multiplying the EPS index of emissions produced from 1 litre of fuel. From the calculations in Table 2, the emission value per litre of diesel fuel is 0.364 EUR. The value of emissions from fuel use is calculated based on the distance traveled. The distance achieved with 1 litre of fuel when transporting products is 5 km for small trucks and 3 km for large trucks (Ministry of Public Works, 2005). Therefore for every 1 litre of diesel fuel used, a cost of 0.364 ELU or 5,874.60 IDR is charged for the exhaust emissions.

Substance	Emission (kg)		EPS Index (ELU/kg)	EPS defaults methods (ELU)
	1 kg of Fuel	1 litre of Fuel		
CO_2	3.17×10^{0}	2.70×10^{0}	1.08×10^{-1}	2.91×10^{-1}
SO_2	2.60×10^{-2}	2.21×10^{-2}	3.27×10^{0}	7.23×10^{-2}
Hg	2.00×10^{-8}	1.70×10^{-8}	6.14×10^{1}	1.04×10^{-6}
Pb	1.10×10^{-7}	9.35×10^{-8}	2.91×10^{3}	2.72×10^{-4}
Total				3.64×10^{-1}

Table 2. Emission Index and Compound Value in ELU (Indrianti & Rustikasari, 2010)

4.2. Calculation Results of Mathemathical Model

The parameters used as inputs from the mathematical model built are shown in Table 3. The parameter values are sourced from primary data resulting from a field survey. This secondary data is a literature review from previous research or other related sources such as the Ministry of Environment and Forestry of Yogyakarta Province, the Center for Controlling the Development of the Java Ecoregion, and the RJ E-waste Community. In addition, several parameters resulting from calculations, such as fixed costs for PCC and SCC, transportation costs, and environmental impact costs from transportation and recycling activities.

Based on the results of questionnaires distributed to 334 respondents, as many as 244 respondents stated that they are willing to collect waste to a collection center provided by the government if given incentives; the rest are willing to collect without expecting incentives. So, 26.9% are willing to bring to the PCC without incentives. The results of calculations using Solver software from Microsoft Excel obtained decision variables with advantages/disadvantages that will be obtained from the management of smartphone waste supply in Yogyakarta Province per month, shown in Figure 3.

Based on the survey, informal recyclers will value smartphone waste at 7,000 IDR per unit, so informal collectors will choose to sell it to informal channel rather than than the formal one with no incentives. If there is no incentive for those who collect at PCC, the total loss borne from the supply chain for supply management of smartphone waste/waste in Yogyakarta Province per month is 1.891×10^{13} IDR, which is obtained from the accumulated profit minus the environmental impact costs in Figure 3. This tremendous loss is due to the enormous environmental impact cost of informal recycling activities, which is 1.896×10^{13} IDR. Due to this enormous value, the cost of environmental impact from transportation activities is 2.04 × 10^6 IDR, which becomes meaningless. Moreover, the benefits obtained cannot cover the costs of the environmental impact caused.

Parameter	Value	Parameter	Value
SP_{puit}	1,000,000 IDR/unit	FC_i	1,250,000,000 IDR/month
$I_{puc(p)t}$	10,000 IDR/unit	$FC_{c(p)}$	3,875,000 IDR/month
$SP_{pur(i)t}$	7,000 IDR/unit	$FC_{c(s)}$	1,666,666.67 IDR/month
SP_{pibt}	1,241,986.50 IDR/unit	$FC_{r(f)}$	1,581,611,111.11 IDR/day
$I_{pic(p)t}$	10,000 IDR/unit	$FC_{r(i)}$	2,500,000 IDR/month
$SP_{q(Au)r(i)st}$	832,008.38 IDR/gr	$DC_{pr(f)t}$	200 IDR/unit
$SP_{q(Au)r(f)st}$	832,008.38 IDR/gr	$RC_{pr(f)t}$	2,647.62 IDR/unit
$SP_{q(Ag)r(f)st}$	11,111.74 IDR/gr	$RC_{pr(i)t}$	1,630.81 IDR/unit
$SP_{q(Pd)r(f)st}$	954,199.89 IDR/gr	RC_{pith}	29,892.45 IDR/unit
$SP_{q(Pt)r(f)st}$	484,651.13 IDR/gr	$L_{c(p)c(s)}$	572.8 km
$SP_{q(Ni)r(f)st}$	277.64 IDR/gr	$L_{r(f)b}$, $L_{r(f)x}$	0
$SP_{q(Cu)r(f)st}$	138.55 IDR/gr	$L_{c(s)r(f)}$	578.9 km
$SP_{q(Pb)r(f)st}$	33.76 IDR/gr	$\alpha_{c(p)c(s)}$	5 litre/ km
$SP_{q(Sn)r(f)st}$	531.70 IDR/gr	$\alpha_{c(s)r(f)}$	3 litre/ km
$SP_{q(Sb)r(f)st}$	118,86 IDR/gr	P_{bbm}	11,150 IDR/litre
$HC_{pc(p)t}$	0	β	5,874.60 IDR
$HC_{pc(s)t}$	200 IDR/unit	$VC_{c(p)c(s)}$	5 tons
$HC_{pr(f)t}$	200 IDR/unit	$VC_{c(s)r(f)}$	12 tons
$HC_{pr(i)t}$	0	$ERC_{pr(f)t}$	0
HC_{pit}	25.000 IDR/unit	$ERC_{pr(i)t}$	644,074,158.75 IDR/unit

Table 3. Model Parameter Value

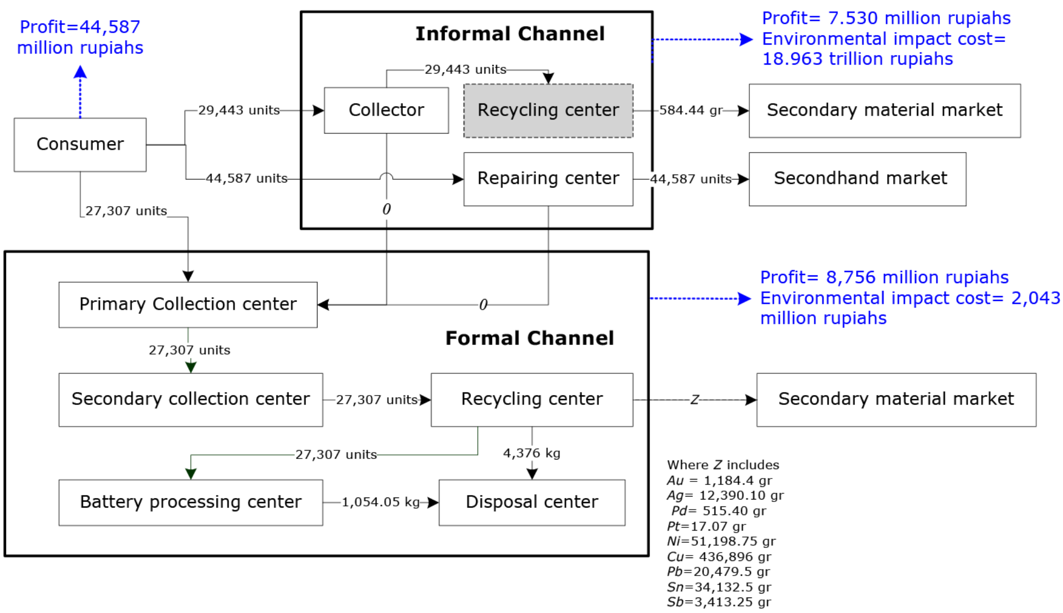

Figure 3. Optimal Solution Without Incentive

Besides, intangible profit is generated due to the savings in metal refining costs compared to natural mining (virgin mining). Virgin mining costs 7x more than smartphone waste recycling to get metal material in the same quantity. In this scenario, the number of products reused and recycled in the formal channel is 71,893 units, so it will save natural mining costs of 1.33×10^9 IDR, which is obtained by multiplying this amount by the savings per product 18.53×10^6 IDR.

The regional government is the party responsible for providing PCC and SCC and transportation from PCC to SCC. The regional government must pay the costs of 18.17×10^6 IDR per month. With a formal recycling center profit of 21.04×10^6 IDR, the cost to the regional government is 12.28×10^6 IDR/month, and the transportation cost of transporting waste is 1.29×10^6 IDR. The profit received from the formal channel to manage the waste supply of Yogyakarta Province per month is 8.76×10^6 IDR. The profit consumers receive is $44{,}587 \times 10^9$ IDR, which is the selling price to the repair center. The profit received by the informal channel is 7.53×10^9 IDR per month is the accumulation of profits from the sale of used smartphones of 7.1×10^9 IDR, the sale of secondary gold metals from informal recycling is 2.32×10^8 IDR, and the profit received by informal collectors is 2.06×10^8 IDR per month from the selling price of electronic waste in informal recycling. The profit received by the formal recycling center is small because the supply that goes into this line is also tiny.

In this network scenario, the profit from the whole supply chain will be maximized if the consumer/informal collector/repairing center is willing to collect it at the primary collection center (PCC) if the used smartphone is damaged or not sold in the secondhand market. Based on the field survey, the informal channel is currently valued at 7,000 IDR for one unit of smartphone waste. If given incentives with a value is greater than the purchase price in informal recycling channels, consumers/informal collectors will switch to channeling their electronic waste to formal channels. Thus, the second scenario in this network was developed by providing an incentive of 10,000 IDR per unit for those willing to collect smartphone waste to PCC. In this scenario, the incentive may be the reward and the driving factor the consumer is willing to collect their waste. When there is an incentive, consumers will be attracted to collect it so that used products stay in the hands of of informal recyclers. Based on the results of the running solver, the decision variables, the profit to be received from the management of the waste supply/smartphone waste in Yogyakarta Province per month, and the overall illustration in Figure 4. The profit received by the formal channel to manage the waste supply of Yogyakarta Province per month is 1.165×10^9 IDR. The profit received by consumers is 44.680×10^9 IDR. The profit received by the informal channel is 7.386×10^9 IDR per month. The benefits received in the formal channel appear smaller than in the informal and consumer channels. However, the formal recycling center facility can serve the recycling of the entire smartphone waste supply in Indonesia due to its enormous capacity of 350 thousand tons per year. If the total supply of waste in Indonesia goes into the formal channel, this channel will receive a profit of more than 75×10^9 IDR per month. The profit value from this channel is quite promising.

Based on the calculation results, when there is no incentive to collect at PCC, the total supply of smartphone waste per month in Yogyakarta province is 101,336 units; 44% of them go to repairing centers, 27% go to PCC, and the remaining 29% go to an informal recycling center. The total loss that will be borne from the entire network of actors in the supply chain for management is 1.891×10^{13} IDR. When there is an incentive policy, 44% of the total supply goes to the repairing center, the remaining 56% goes to PCC, and the total profit to be earned is 5.529×10^{10} IDR. The comparison of benefits received from supply management per month between incentives and without incentives is shown in Table 4. Positive numbers indicate profits to be received, while negative numbers indicate costs to be incurred.

A negative value in Table 4 indicates that the activity causes environmental pollution. Activities that harm the environment are informal transportation and recycling activities. The negative environmental impact caused by informal recycling practices is enormous; eventually, this cost dominates the total cost if no incentives are given. Suppose the value of the environmental impact needs to be quantified in terms of money. In that case, providing incentives is still more profitable because the total profit received with incentives is 1.832×10^9 IDR higher than without incentives.

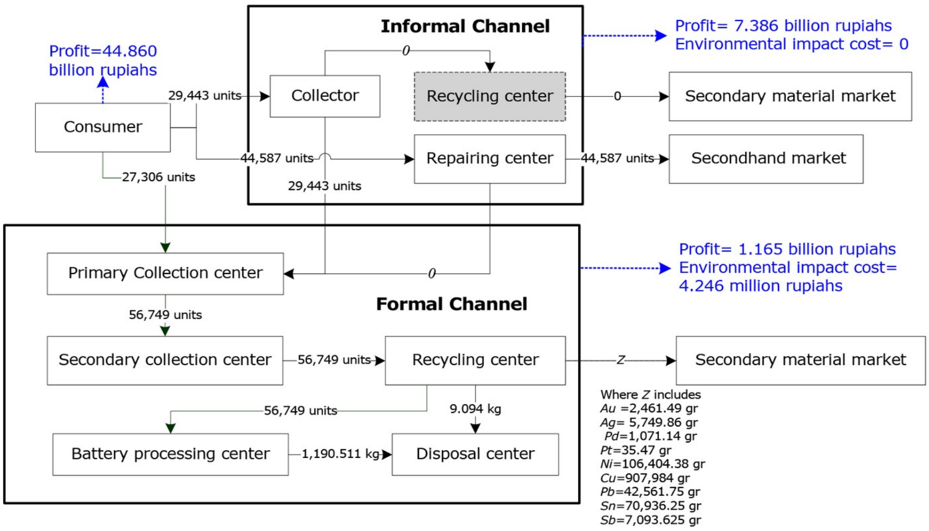

Figure 4. Optimal Solutions With Incentives

Revenue or Cost	With Incentive (IDR)	Without Incentive (IDR)
Informal channel	7,386,000,000	7,530,000,000
Consumers	44,860,000,000	44,587,000,000
Formal channel	1,167,000,000	800,000
Intangible profit	1,878,000,000	1,332,000,000
Transportation activity	-4,000,000	-2,000,000
Informal recycling activities	0	-18,963,475,000,000
Formal recycling activities	0	0
Total profit	55,287,000,000	-18,910,019,000,000

Table 4. Comparison of Revenues per Month between With and Without Incentive

4.3. Sensitivity Analysis

Sensitivity analysis (model behavior) was carried out by changing several model parameters. Changes were made to the number of products sold to repair centers and the number of product supplies from consumers who entered the formal channel. Figure 5 shows the profit the repairing center will receive if total waste supply percentage of Yogyakarta Province per month that enters the repairing center from consumers is increased/decreased.

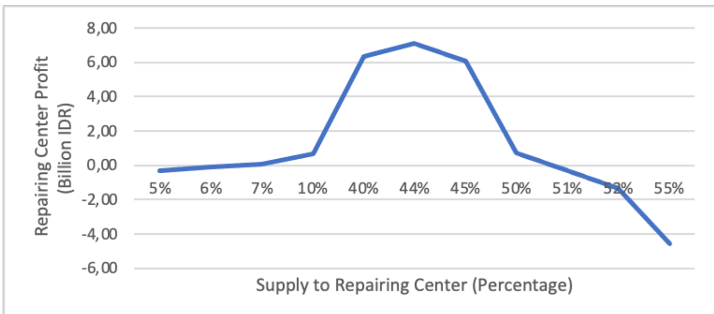

Figure 5. Profit Repairing Center Based on Total Waste Supply Percentage

Figure 5 shows that the profit for the repairing center will be optimal when the number of end-products sold to the repairing center is 44% of the total supply. This condition is because the final consumer for the secondhand market is around 44%, so if the repairing center buys a used smartphone from more than 44% of users, the remaining unsold ones will be collected to the primary collection center and considered waste at 10,000 IDR per unit. While the acquisition cost for the product is 1×10^6 IDR, the more products are bought, the more are lost. Meanwhile, from the consumer's point of view, the more products sold at the repairing center, the higher the profit to be gained because the product still has a relatively high selling price. Figure 6 also shows that the repairing center is feasible or profitable if at least a supply of secondhand products comes in at 7% of the total supply or 7,000 units.

The behavioral analysis of the model is then carried out by changing the amount of supply that enters the formal channel. Consumers will generally sell their products if they still sell well at the repair center because it provides a much greater profit. However, the repair center will limit what is given from consumers to no more than 44%, so the amount that goes to the repair center will be maximized by 44% of the total supply. For example, if the total supply is 101,336 units, 44,587 units will go to the repairing center. By providing more significant incentives than the informal channel, it is hoped that the remaining 56% of the supply will enter the formal channel, both from consumers and informal collectors. When there is no incentive, the formal channel is feasible if the incoming waste supply is at least 27% of the total supply. Figure 6 shows the amount of waste supplied from Yogyakarta Province per month and the profit that will be received by the formal channel if given an incentive of 10,000 IDR per unit.

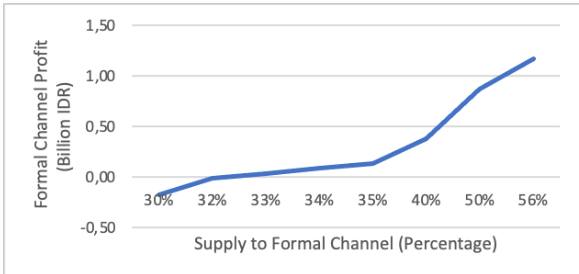

Figure 6. Formal Channel Profit Based on Total Waste Supply Percentage

The advantages of the formal channel are obtained from the benefits of the formal recycling center minus the costs incurred by the local government. Incentives for consumers and the cost of transporting waste from PCC to SCC is 1.277×10^6 IDR per month is the responsibility of the Regional Government, for the cost of transporting waste from SCC to the recycling company is 1.291×10^6 IDR per month is the responsibility of the licensed recycling company.

When the amount of supply that enters the formal channel is more significant, the profit to be received by the formal channel is also greater. Formal recycling practices are environmentally friendly and harmless to the environment, as indicated by the negative eco-cost value. Based on Figure 6, the formal channel is feasible/profitable if at least 33% of the total monthly waste supply from Yogyakarta Province goes to the formal channel. If less than 33% of the waste goes into the formal channel, then the formal channel will lose; the income received is smaller than the costs because the investment costs are very high.

4.4. Design of Electronic Waste Management Implementation in Indonesia

Based on the analysis of consumer behavior after using smartphones, regulation/government drivers are the factors that most influence consumers' intentions to participate in e-waste collection programs (Sari et al., 2021b). As suppliers of raw materials and smartphone waste, consumers are critical in making this management network work. The existence of regulations will force consumers to collect smartphone waste at the collection center that has been provided. The regulation will be able to change consumer behavior, so regulation and supervision are needed for the success of the proposed management model. One of the successful government programs with regulations is the Indonesian government's program to reduce the volume of plastic waste. The government makes regulations that prohibit the use of plastic bags that are enforced in shopping centers and the use of plastic straws. With this regulation, shopping centers cannot provide plastic bags, so consumers must prepare and bring them whenever they go shopping. Some restaurants also no longer provide plastic straws. The prohibition on bottled drinking water has also changed people's behavior, encouraging them to bring a tumbler/bottle outside the home. This phenomenon shows that government drivers have succeeded in changing people's behavior. Even consumers who use electronics in Japan must pay us to collect their used electronic products; this habit is formed by regulation. The influence of the law on product RL has been seen in the electronics industry. The environmental problems associated with this disposal practice trigger the state to issue rules and regulations governing waste practices (Rosov, Mallin & Cahoon, 2020). Legislation forces manufacturers in many industries to establish safe product recovery and disposal systems (Mwanza, Mbohwa & Telukdarie, 2017). Compliance with regulations is essential in motivating recycling behavior (Mak, Yu, Wang, Hsu, Tsang, Li et al., 2019).

In order to effectively tackle the problem of e-waste, various countries, regardless of whether they are developed or developing, have made individual regulations, laws, regulations, and initiatives to tackle the enormous growing problem of e-waste. However, the developed countries, namely the European Union, the United States of America, and other central Asian shareholder developing countries have contributed to the product initiatives. These regulatory products include the Waste Electrical and Electronic Equipment (WEEE) Directive, Restriction of Hazardous Substances (RoHS) Directive, EU Directive on Energy-using-Products (EuP), EU Directive on Registration, Evaluation and Authorization of Chemicals (REACH), E-waste regulations in Japan, China, India, Korea, United States, Canada, and other many nations Basel Convention/s, Basel Convention Partnership on the ESM of E-waste in the Asia-Pacific region Mobile Phone Partnership Initiative (MPPI), Partnership for Action on Computing Equipment (PACE), StEP Initiative and Regional 3R Forum in Asia (Kumar & Singh, 2013). In comparison, the legal basis for the electronic waste management system in Indonesia, according to Simatupang (2018), includes Law Number 32 of 2009 concerning Environmental Protection and Management, Law Number 18 of 2008 concerning Waste Management, Presidential Decree 61/1993 concerning Ratification of the Basel Convention, Presidential Decree 47/2005 concerning Amendments to the Basel Convention concerning the Supervision of Transboundary Movements of Hazardous Waste and Its Disposal and Government Regulation Number 101/2014 concerning Hazardous Waste Management.

Implementation of the results in the field requires support from the government to encourage people to be willing to collect electronic waste at the collection center that has been provided. The results of the calculations that have been carried out are in line with the management plan that the government will carry out. The Ministry of Environment and Forestry has prepared a Ministerial Regulation on Electronic Waste Management, collaborating between informal and formal channels. Currently, informal management is developing, so in the design, informal players are still allowed to participate in waste management but only for collection and repair. At the same time, further processing, such as recycling, must be carried out by formal channels with considering of environmental impacts as shown in Figure 7. The electronic waste management channel follows the draft Regulation of the Minister of Environment and Forestry concerning Electronic Waste.

A survey conducted by the government confirms the results of this study. Based on the survey results, consumers expect a collection system and compensation mechanism when handing over electronic waste. In addition, there is the extension of producer responsibility at the point of rights and obligations in the draft regulation. Each electronic goods producer was responsible for distributing electronic waste to authorized recyclers or destroyers to ensure environmentally friendly waste management. Expanding the producer's responsibility is to protect the environment by implementing a takeback mechanism for electronic waste and establishing a producer responsibility consortium or electronic waste fund management agency. When producers have a high commitment to fund management institutions, the incentives given to consumers should be of more excellent value because the profit received by formal recyclers is obtained from selling secondary materials and subsidies from the fund management agency.

In the designed network, the cost of transporting smartphone waste from PCC to SCC is the responsibility of the Regional Government; this is in line with Government Regulation No. 27 of 2020 concerning Specific Waste Management. Local Governments are responsible for household segregation, incentives, and transporting specific waste containing hazardous and toxic materials (B3), including transportation from dropbox (PCC) to temporary waste storage (SCC). Meanwhile, for the transportation of waste from SCC to the recycling company, it is the responsibility of the licensed recycling company following Government Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management and Regulation of the Minister of Environment and Forestry No. 6 of 2021. The strategy for managing electronic waste and the flow of waste management processes B3 waste management have been. The Ministry of Environment will carry them out.

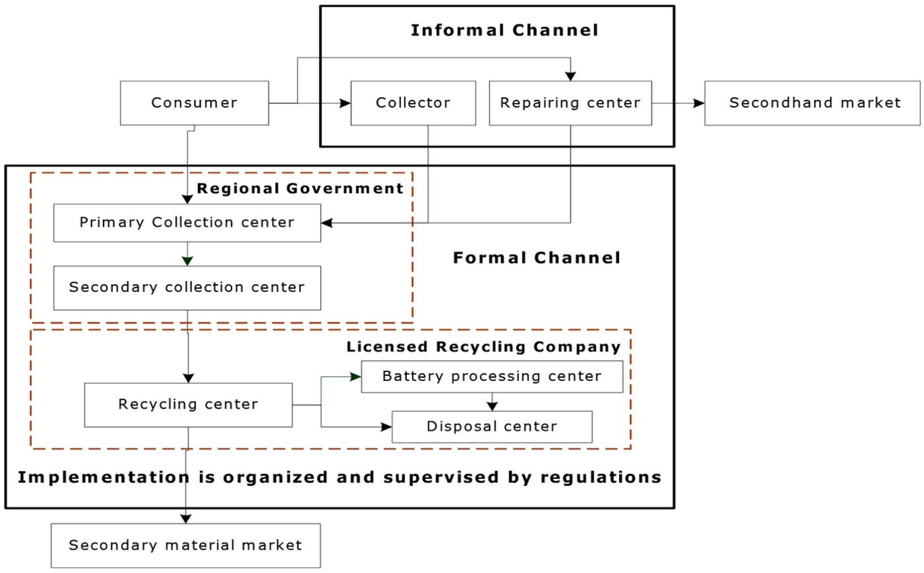

Figure 7. Possible Design Results to be Implemented

In managing electronic waste in other countries, incentives are one of the strategies used and considered quite effective to attract consumers to be willing to collect their electronic waste. For example, incentives are a driving factor for minimizing waste production in Malaysia. The incentives provided will increase the collection of smartphones in the early stages of a full recycling facility (Soo, Featherston & Doolan, 2013). Monetary incentives act as the most efficient incentives for the success of takeback services in Malaysia (Senawi & Sheau-Ting, 2016) and in China (Li, Yang, Song & Lu, 2012). In developing countries, combining regulation with an incentive system will increase the success of implementing a new regulation (Halim & Suharyanti, 2019; Zeng, Duan, Wang & Li, 2017; Shevchenko, Laitala & Danko, 2019). Incentives will increase collection rates (Shevchenko et al., 2019), one of which is in the UK (Ongondo & Williams, 2011). Economic reasons (incentives) are the motivation to implement RL because incentives are one way to stimulate residents to sort and place waste properly at the designated collection point (Jiang, Van Fan, Zhou, Zheng, Liu & Klemeš, 2020). Society places economic incentives as the primary driver of waste recycling (Mak et al., 2019). Incentives can be a strategy to invite consumers to participate in the e-waste collection process for the short and medium term. In contrast, in the long term, when consumers have awareness and dispose of them with the right system, incentives may become unnecessary (Soo et al., 2013; Yunita, Zagloel, Ardi & Zulkarnain, 2019).

5. Conclusion

Collaborating formal and informal channels under government regulation and supervision makes the E-waste management network model provides the most significant total benefit for the supply chain regarding economic and environmental aspects. Supply chain actors will benefit from the proposed management network if this network is successful. Incentives are one of the strategies that can be used to invite consumers/informal collectors to be willing to collect them at a collection center; therefore, the provision of incentives is a stimulant so that the community is willing to participate in a strategy that can be considered to support the success of the built network practice. By providing incentives of 10,000 IDR for those who collect waste through formal channels, the supply chain will profit 5.529×10^{10} IDR per month for waste from Yogyakarta Province. Consumers' most extensive profit composition was 4.486×10^{10} IDR for the informal channel, 7.386×10^{9} IDR obtained from the repairing center 1.165×10^{9} IDR for the formal channel. An intangible profit will be received in 1.878×10^{9} IDR , this profit is generated due to the savings in metal refining costs compared to virgin mining. Formal channels provide more excellent benefits but also require significant investment costs. This channel feasible/profitable if at least 33% of the total supply of waste/waste per month from Yogyakarta Province enters the formal channel. Providing incentives as a stimulant so that the community is willing to participate is a strategy that can support the success of the built network practice. The model designed is deterministic. Therefore, it can be developed into a probabilistic model for further research to represent more real cases in the field.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This research is part of a PhD study that was financially supported by the BUDI DN Grant from the Lembaga Pengelola Dana Penelitian (LPDP), Ministry of Finance, and Ministry of Education and Culture, Republic of Indonesia, grant number KET-193/LPDP.4/2020.

References

Agrawal, S., Singh, R.K., & Murtaza, Q. (2016). Prioritizing critical success factors for reverse logistics implementation using fuzzy-TOPSIS methodology. *Journal of Industrial Engineering International,* 12, 15-27. Available at: https://link.springer.com/article/10.1007/s40092-015-0124-8

Alshamsi, A., & Diabat, A. (2017). A Genetic Algorithm for Reverse Logistics network design: A case study from the GCC. *Journal of Cleaner Production,* 151, 652-669. https://doi.org/10.1016/j.jclepro.2017.02.096

Alumur, S.A., Nickel, S., Saldanha-da-Gama, F., & Verter, V. (2012). Multi-period reverse logistics network design. *European Journal of Operational Research*, 220(1), 67-78. https://doi.org/10.1016/j.ejor.2011.12.045

Andarani, P., & Goto, N. (2014). Potential e-waste generated from households in Indonesia using material flow analysis. *Journal of Material Cycles and Waste Management*, 16(2), 306-320. https://doi.org/10.1007/s10163-013-0191-0

Antam, 2015, *Highlights Kinerja*. Available at: https://cdn.indonesia-investments.com/bedrijfsprofiel/217/Aneka-Tambang-Antam-Annual-Report-2015-Indonesia-Investments.pdf (Accessed: February 2021).

Ardente, F., Calero-Pastor, M., Mathieux, F., & Talens-Peiró, L. (2015). Analysis of end-of-life treatments of commercial refrigerating appliances: Bridging product and waste policies. *Resources, Conservation and Recycling,* 101, 42-52. https://doi.org/10.1016/j.resconrec.2015.05.005

Arya, S., & Kumar, S. (2020). E-waste in India at a glance: Current trends, regulations, challenges and management strategies. *Journal of Cleaner Production*, 271, 122707. https://doi.org/10.1016/j.jclepro.2020.122707

Ayvaz, B., Bolat, B., & Aydin, N. (2015). Stochastic reverse logistics network design for waste of electrical and electronic equipment. *Resources, Conservation and Recycling*, 104, 391-404. https://doi.org/10.1016/j.resconrec.2015.07.006

Bal, A., & Satoglu, S.I. (2018). A goal programming model for sustainable reverse logistics operations planning and an application. *Journal of Cleaner Production*, 201, 1081-1091. https://doi.org/10.1016/j.jclepro.2018.08.104

Baldé, C.P., Forti, V., Gray, V., Kuehr, R., & Stegmann, P. (2017). *The Global E-waste Monitor 2017,* United Nations University (UNU). Available at: https://collections.unu.edu/eserv/UNU:6341/Global-E-waste_Monitor_2017__electronic_single_pages_.pdf (Accessed: June 2019).

Banguera, L.A., Sepúlveda, J.M., Ternero, R., Vargas, M., & Vásquez, Ó.C. (2018). Reverse logistics network design under extended producer responsibility: The case of out-of-use tires in the Gran Santiago city of Chile. *International Journal of Production Economics*, 205, 193-200. https://doi.org/10.1016/j.ijpe.2018.09.006

Battery University (2021). *Learn about disposal and how toxic material can continue to be used in batteries if recycled.* Available at: https://batteryuniversity.com/article/bu-705-how-to-recycle-batteries (Accessed: November 2021).

Blass, V.D., Fuji, M., Neira, J., Favret, L., Mahdavi, S., Miller, R. et al. (2006). *End-of-life management of cell phones in the United States*. Thesis. Environmental Science and Management Department, University of California. https://doi.org/10.1109/ISEE.2008.4562849 (Accessed: January 2021).

Budijati, S.M. (2016). *Model pengelolaan reverse logistics jalur formal dan informal serta mengakomodasi perilaku konsumen*. Dissertation. Departement of Mechanical and Industrial Engineering, Universitas Gadjah Mada, Indonesia.

Central Bureau of Statistics (2021). *Daerah Istimewa Yogyakarta Province in Figure 2021*. Available at: https://yogyakarta.bps.go.id (Accessed: October 2021).

ComputerCare (2019). *Your Phone's Lifespan is Five Years – Here's How to Keep it Going!* Available at: https://computercare.net/2019/12/your-phones-lifespan-is-five-years-heres-how-to-keep-it-going/ (Accessed: November 2021).

Dat, L.Q., Truc-Linh, D.T., Chou, S.Y., & Yu, V.F. (2012). Optimizing reverse logistic costs for recycling end-of-life electrical and electronic products. *Expert Systems with Applications*, 39(7), 6380-6387. https://doi.org/10.1016/j.eswa.2011.12.031

Doan, L.T.T., Amer, Y., Lee, S.H., Phuc, P.N.K., & Dat, L.Q. (2019). A comprehensive reverse supply chain model using an interactive fuzzy approach – A case study on the Vietnamese electronics industry. *Applied Mathematical Modelling*, 76, 87-108. https://doi.org/10.1016/j.apm.2019.06.003

Dutta, P., Mishra, A., Khandelwal, S., & Katthawala, I. (2020). A multiobjective optimization model for sustainable reverse logistics in Indian E-commerce market. *Journal of Cleaner Production*, 249, 119348. https://doi.org/10.1016/j.jclepro.2019.119348

Firdaus, A.H.F., & Santoso (2020). *Sistem bahan bakar motor diesel*. Malang: Polinema Press.

Geyer, R., & Blass, V.D. (2010). The economics of cell phone reuse and recycling. *International Journal of Advanced Manufacturing Technology*, 47(5-8), 515-525. https://doi.org/10.1007/s00170-009-2228-z

Gomes, M.I., Barbosa-Povoa, A.P., & Novais, A.Q. (2011). Modelling a recovery network for WEEE: A case study in Portugal. *Waste Management*, 31(7), 1645-1660. https://doi.org/10.1016/j.wasman.2011.02.023

Govindan, K., Paam, P., & Abtahi, A.R. (2016). A fuzzy multi-objective optimization model for sustainable reverse logistics network design. *Ecological Indicators*, 67, 753-768. https://doi.org/10.1016/j.ecolind.2016.03.017

Guo, J. Liu, X., & Jo, J. (2017). Dynamic joint construction and optimal operation strategy of multi-period reverse logistics network: a case study of Shanghai apparel E-commerce enterprises. *Journal of Intelligent Manufacturing,* 28, 819-831. https://doi.org/10.1007/s10845-015-1034-8

Guvendik, M. (2014). *From Smartphone to Futurephone: Assessing the Environmental Impacts of Different Circular Economy Scenarios of a Smartphone Using LCA*. Master Thesis. Industrial Ecology at Delft University of Technology and Leiden University. Available at: http://resolver.tudelft.nl/uuid:13c85c95-cf75-43d2-bb61-ee8cf0acf4ff

Hageluken C. (2006). Improving metal returns and eco-efficiency in electronics recycling. *Proceedings of the 2006 IEEE Conference* (218-223). Scottsdale (USA). https://doi.org/10.1109/ISEE.2006.1650064

Halim, L., & Suharyanti, Y. (2019). E-waste: Current Research and Future Perspective on Developing Countries. *International Journal of Industrial Engineering and Engineering Management*, 1(2), 25-41. https://doi.org/10.24002/ijieem.v1i2.3214

Hanisah, K., Kumar, S., & Tajul, A. (2013). The Management of Waste Cooking Oil: A Preliminary Survey. *Health and the Environment Journal*. 4(1), 76-81. Available at: https://www.researchgate.net/publication/320823701_The_Management_of_Waste_Cooking_Oil_A_Preliminary_Survey (Accessed: January 2019).

Indrianti, N., & Rustikasari, A.G. (2010). A Reverse Logistics Model for Battery Recycling Industry. *Proceeding of Asia Pacific Industrial Engineering and Management Systems Conference*. Melaka (Malaysia).

Jakarta Smart City (n.d.). *Truk Compactor: Alat Pengangkut Sampah yang Lebih Ramah Lingkungan*. https://smartcity.jakarta.go.id/blog/204/truk-compactor-alat-pengangkut-sampah-yang-lebih-ramah-lingkungan (Accessed: November 2021)

Jiang, P., Van Fan, Y., Zhou, J., Zheng, M., Liu, X., & Klemeš, J.J. (2020). Data-driven analytical framework for waste-dumping behaviour analysis to facilitate policy regulations. *Waste Management*, 103, 285-295. https://doi.org/10.1016/j.wasman.2019.12.041

John, S.T., Sridharan, R., Ram-Kumar, P.N., & Krishnamoorthy, M. (2018). Multi-period reverse logistics network design for used refrigerators. *Applied Mathematical Modelling*, 54, 311-331. https://doi.org/10.1016/j.apm.2017.09.053

Kementarian Energi dan Sumber Daya Mineral (n.d.). Available at: https://www.minerba.esdm.go.id/ (Accessed: December 2021).

Keyvanshokooh, E., Fattahi, M., Seyed-Hosseini, S.M., & Tavakkoli-Moghaddam, R. (2013). A dynamic pricing approach for returned products in integrated forward/reverse logistics network design. *Applied Mathematical Modelling*, 37(24), 10182-10202. https://doi.org/10.1016/j.apm.2013.05.042

Kumar, U., & Singh, D.D.N. (2013). E-Waste Management through Regulations. *International Journal of Engineering Inventions*, 3(2), 6-14. Available at: http://www.ijeijournal.com (Accessed: June 2020).

KursDollar (n.d.). Available at: https://kursdollar.org (Accessed: December 2021).

Kuşakcı, A.O., Ayvaz, B., Cin, E., & Aydın, N. (2019). Optimization of reverse logistics network of End of Life Vehicles under fuzzy supply: A case study for Istanbul Metropolitan Area. *Journal of Cleaner Production*, 215, 1036-1051. https://doi.org/10.1016/j.jclepro.2019.01.090

Li, B., Yang, J., Song, X., & Lu, B. (2012). Survey on Disposal Behaviour and Awareness of Mobile Phones in Chinese University Students. *Procedia Environmental Sciences*, 16, 469-476. https://doi.org/10.1016/j.proenv.2012.10.064

Liao, T.Y. (2018). Reverse logistics network design for product recovery and remanufacturing. *Applied Mathematical Modelling*, 60, 145-163. https://doi.org/10.1016/j.apm.2018.03.003

Mak, T.M.W., Yu, I.K.M., Wang, L., Hsu, S.C., Tsang, D.C.W., Li, C.N. et al. (2019). Extended theory of planned behaviour for promoting construction waste recycling in Hong Kong. *Waste Management*, 83, 161-170. https://doi.org/10.1016/j.wasman.2018.11.016

Malaidji, E., Anshariah, & Budiman, A.A. (2018). Analisis proksimat, sulfur, dan nilai kalor dalam penentuan kualitas batubara di Desa Pattappa Kecamatan Pujananting Kabupaten Barru Provinsi Sulawesi Selatan. *Jurnal Geomine*, 6(3), 131-137. https://doi.org/10.33536/jg.v6i3.244

Mattsson, J. (2012). *Life Cycle Impact Assessment – A Study of The EPS Method for Use within SCA*. Master of Science thesis. Department of Energy and Environment, Chalmers University of Technology. Gö teborg, Sweden.

Messmann, L., Helbig, C., Thorenz, A., & Tuma, A. (2019). Economic and environmental benefits of recovery networks for WEEE in Europe. *Journal of Cleaner Production*, 222, 655-668. https://doi.org/10.1016/j.jclepro.2019.02.244

Ministry of Public Works (2005). *Estimation of Operational Cost on Vehicles*. Available at: https://binamarga.pu.go.id/uploads/files/773/pedoman-perhitungan-biaya-operasi-kendaraan-bagian-i-biaya-tidak-tetap-running-cost.pdf (Accessed: July 2021).

Mwanza, B.G., Mbohwa, C., & Telukdarie, A. (2017). Drivers of reverse logistics in the plastic industry: Producer's perspective. *Proceedings of the International Conference on Industrial Engineering and Operations Management* (1037-1045). Bogota, Colombia.

Navazo, J.M.V., Méndez, G.V., & Peiró, L.T. (2014). Material flow analysis and energy requirements of mobile phone material recovery processes. *International Journal of Life Cycle Assessment*, 19(3), 567-579. https://doi.org/10.1007/s11367-013-0653-6

Nurhayati-Wolff, H. (2020). *Share of population owning a mobile phone in Indonesia from 2010 to 2019*. Available at: https://www.statista.com/statistics/1084069/indonesia-share-of-population-owning-a-mobile-phone/ (Accessed: March 2020).

Ongondo, F.O., & Williams, I.D. (2011). Mobile phone collection, reuse and recycling in the UK. *Waste Management*, 31(6), 1307-1315. https://doi.org/10.1016/j.wasman.2011.01.032

Rahimi, M., & Ghezavati, V. (2018). Sustainable multi-period reverse logistics network design and planning under uncertainty utilizing conditional value at risk (CVaR) for recycling construction and demolition waste. *Journal of Cleaner Production*, 172, 1567-1581. https://doi.org/10.1016/j.jclepro.2017.10.240

Ripa, M., Buonaurio, C., Mellino, S., Fiorentino, G., & Ulgiati, S. (2014). Recycling waste cooking oil into biodiesel: A life cycle assessment. *International Journal of Performability Engineering*, 10(4), 347-356. Available at: https://www.researchgate.net/publication/262559555

Rosov, K.A., Mallin, M.A., & Cahoon, L.B. (2020). Waste nutrients from U.S. animal feeding operations: Regulations are inconsistent across states and inadequately assess nutrient export risk. *Journal of Environmental Management*, 269, 110738. https://doi.org/10.1016/j.jenvman.2020.110738

Safari, H., Etezadi, S., Moradi-Moghadam, M., & Fathi, M.R. (2021). Maturity evaluation of supply chain procedures by combining SCOR and PST models. *International Journal of Process Management and Benchmarking*, 11(5), 707-724. https://doi.org/10.1504/IJPMB.2021.117283

Sari, D.P., Masruroh, N.A., & Asih, A.M.S. (2021a). Development of an Electronic Reverse Logistics Network Model: A Literature Review. *IOP Conference Series: Materials Science and Engineering, 1096, The 6th International Conference on Industrial, Mechanical, Electrical and Chemical Engineering, ICIMECE,* Solo (Indonesia). https://doi.org/10.1088/1757-899X/1096/1/012020

Sari, D.P., Masruroh, N.A., & Asih, A.M.S. (2021b). Consumer intention to participate in e□ waste collection programs: A study of smartphone waste in Indonesia. *Sustainability (Switzerland)*, 13(5), 2759. https://doi.org/10.3390/su13052759

Sari, D.P., Masruroh, N.A., & Asih, A.M.S. (2021c). Factors Affecting Consumer Acquisition of Secondhand Smartphone in Indonesia. *IEEE International Conference on Industrial Engineering and Engineering Management* (416-420). Songapore. https://doi.org/10.1109/IEEM50564.2021.9673092

Sari, D.P., Masruroh, N.A., & Asih, A.M.S. (2021d). Extended maximal covering location and vehicle routing problems in designing smartphone waste collection channels: A case study of Yogyakarta Province, Indonesia. *Sustainability (Switzerland)*, 13(16), 8896. https://doi.org/10.3390/su13168896

Sari, D.P., Masruroh, N.A., & Asih, A.M.S. (2023). Eco-efficiency comparative analysis of informal and formal smartphone recycling practices using life cycle assessment. *International Journal on Advanced Science, Engineering & Information Technology*, 13(3), 1108-1117. https://doi.org/10.18517/ijaseit.13.3.17452

Senawi, N.H., & Sheau-Ting, L. (2016). Attributes to facilitate e-waste recycling behaviour. *MATEC Web of Conferences*, 66, 4-8. https://doi.org/10.1051/matecconf/20166600058

Shevchenko, T., Laitala, K., & Danko, Y. (2019). Understanding consumer e-waste recycling behavior: Introducing a new economic incentive to increase the collection rates. *Sustainability (Switzerland)*, 11(9), 2656. https://doi.org/10.3390/su11092656

Simatupang, T. M. (2018). *Sistem Pengelolaan Sampah Elektronik* (SPSE). Available at: https://www.slideshare.net/slideshow/sistem-pengelolaan-sampah-elektronik-spse/102602731 (Accessed: February 2021).

Sohrabi, T., Etemad, M., & Fathi, M.R. (2018). Mathematical modeling of Green closed loop supply chain network with consideration of supply risk: Case Study. *Journal of Advanced Mathematical Modeling*, 7(2), 103-122. https://doi.org/10.22055/jamm.2018.18354.1303

Soleimani, H., & Govindan, K. (2014). Reverse logistics network design and planning utilizing conditional value at risk. *European Journal of Operational Research*, 237(2), 487-497. https://doi.org/10.1016/j.ejor.2014.02.030

Soo, V.K., Featherston, C., & Doolan, M. (2013). E-waste Assessment in Malaysia. *20th CIRP International Conference on Life Cycle Engineering* (389-395). Singapore. https://doi.org/10.1007/978-981-4451-48-2_64

Sugandini, D., Muafi, M., Susilowati, C., Siswanti, Y., & Syafri, W. (2020). Green supply chain management and green marketing strategy on green purchase intention: SMEs cases. *Journal of Industrial Engineering and Management*, 13(1), 79-92. https://doi.org/10.3926/jiem.2795

Sutanto, A., Yuliandra, B., & Pratama, W. (2017). Manufaktur Yang Berkelanjutan Pada Sampah Elektronik (E-Waste)Di Kota Padang: Tinjauan Kasus Sampah Kulkas. *Jurnal Optimasi Sistem Industri*, 16(1), 1-14. https://doi.org/10.25077/josi.v16.n1.p25-33.2017

Syahban, L. (2018a). *Ke Mana Sampah Elektronik Dibuang*. Available at: https://news.detik.com/x/detail/intermeso/20180119/Ke-Mana-Sampah-Elektronik-Dibuang/ (Accessed: March 2020).

Syahban, L. (2018b). *Tambang Emas di Gunung Sampah*. Available at: https://news.detik.com/x/detail/intermeso/20180119/Tambang-Emas-di-Gunung-Sampah/ (Accessed: March 2020).

Taleizadeh, A.A., Haghighi, F., & Niaki, S.T.A. (2019). Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products. *Journal of Cleaner Production*, 207, 163-181. https://doi.org/10.1016/j.jclepro.2018.09.198

Tokopedia (n.d.a). Available at: https://www.tokopedia.com/multijayakimia/nitric-acid-asam-nitrat-hno3-35kg-ex-belgia (Accessed: December 2021).

Tokopedia (n.d.b). Available at: https://www.tokopedia.com/cv-cepy/hcl-32-pembersih-keramik (Accessed: December 2021).

Tosarkani, B.M., & Amin, S.H. (2018). A multi-objective model to configure an electronic reverse logistics network and third party selection. *Journal of Cleaner Production*, 198, 662-682. https://doi.org/10.1016/j.jclepro.2018.07.056

Tosarkani, B.M., Amin, S.H., & Zolfagharinia, H. (2020). A scenario-based robust possibilistic model for a multi-objective electronic reverse logistics network. *International Journal of Production Economics*, 224, 107557. https://doi.org/10.1016/j.ijpe.2019.107557

Ulya, F.N. (2019). *Berapa Lama Orang Indonesia Ganti Ponsel Baru?* Available at: https://money.kompas.com/read/2019/07/19/074700926/berapa-lama-orang-indonesia-ganti-ponsel-baru- (Accessed: July 2020).

United Nation Environment Program - UNEP (1987). *The montreal protocol on subtances that deplete the ozone layer*. Available at: https://ozone.unep.org/treaties/montreal-protocol (Accessed: May 2019).

Watson, A. (2020). *Device usage increase due to the coronavirus worldwide 2020, by country*. Available at: https://www.statista.com/statistics/1106607/device-usage-coronavirus-worldwide-by-country/ (Accessed: July 2020).

Wongthongchai, J., & Saenchaiyathon, K. (2019). The Key Role of Institution Pressure on Green Supply Chain Practice and the Firm's Performance. *Journal of Industrial Engineering and Management*, 12(3), 432-446. https://doi.org/10.3926/jiem.2994

Yunita, M.T., Zagloel, T.Y.M., Ardi, R., & Zulkarnain (2019). Development of funding model in e-waste management systems for households products in indonesia. *IOP Conference Series: Earth and Environmental Science*, 219(1), 1-6. https://doi.org/10.1088/1755-1315/219/1/012005

Zaenudin, A. (2017). *Berapa Lama Orang Mengganti Ponsel?* Available at: https://tirto.id/berapa-lama-orang-mengganti-ponsel-clBj (Accessed: March 2017).

Zarbakhshnia, N., Soleimani, H., Goh, M., & Razavi, S.S. (2019). A novel multi-objective model for green forward and reverse logistics network design. *Journal of Cleaner Production*, 208, 1304-1316. https://doi.org/10.1016/j.jclepro.2018.10.138

Zeng, X., Duan, H., Wang, F., & Li, J. (2017). Examining environmental management of e-waste: China's experience and lessons. *Renewable and Sustainable Energy Reviews*, 72, 1076-1082. https://doi.org/10.1016/j.rser.2016.10.015

Zeng, X., Mathews, J.A., & Li, J. (2018). Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environmental Science and Technology*, 52(8), 4835-4841. https://doi.org/10.1021/acs.est.7b04909

Zhen, L., Huang, L., & Wang, W. (2019). Green and sustainable closed-loop supply chain network design under uncertainty. *Journal of Cleaner Production*, 227, 1195-1209. https://doi.org/10.1016/j.jclepro.2019.04.098

Article's contents are provided on an Attribution-Non Commercial 4.0 Creative commons International License. Readers are allowed to copy, distribute and communicate article's contents, provided the author's and Journal of Industrial Engineering and Management's names are included. It must not be used for commercial purposes. To see the complete license contents, please visit https://creativecommons.org/licenses/by-nc/4.0/.