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Cost Optimization for Electronic Waste Recovery in a Reverse Logistics Network

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Abstract

INTRODUCTION: The rapid advancement of science and technology has fueled the widespread adoption of electronic devices, ranging from semiconductors to complex electronic circuits. These devices, typically classified into large household appliances, IT and telecommunications equipment, and consumer electronics, have significantly enhanced both the quality of life and operational efficiency in businesses. However, the increasing volume of these electronics has introduced a major challenge: the effective management of electronic waste (e - waste). Without a well - designed system, the accumulation of e - waste can lead to severe environmental and public health consequences.
OBJECTIVES: This study aims to address the pressing issue of e-waste by analyzing the costs associated with its processing and proposing an optimized reverse logistics network. Specifically, the primary goal is to design a system that not only reduces operational costs but also minimizes the environmental footprint associated with e - waste management. By leveraging advanced modeling techniques, the research seeks to provide a practical framework that can be adopted in both industrial and municipal settings.
METHODS: To achieve these objectives, a Mixed - Integer Linear Programming (MILP) model was developed to represent the cost optimization problem associated with e - waste collection and recycling. The model incorporates various stages of the reverse logistics process, including collection, sorting, transportation, and final processing. Its solution was derived using CPLEX optimization software, which allowed for the identification of the most cost - effective network configuration. Sensitivity analyses were conducted to ensure the robustness of the proposed framework, enabling stakeholders to make informed decisions based on different scenarios and constraints.
RESULTS: The MILP model produced an optimized solution that minimizes recovery costs while maximizing the retrieval of reusable components and materials. In addition, the study found that incorporating sustainability factors into the model significantly improved the overall efficiency of the reverse logistics network. The optimized configuration demonstrates the potential of a well - structured reverse logistics system to reduce processing expenses, improve resource efficiency, and encourage the reuse of valuable materials, ultimately contributing to a more circular economy.
CONCLUSION: Improper disposal of electronic waste presents significant environmental and health risks, particularly during the mechanical and chemical treatment of circuit boards. By introducing an optimized reverse logistics model, this study offers a practical solution that reduces processing costs, promotes resource conservation, and supports long - term environmental sustainability. Moreover, the findings underscore the importance of integrating advanced optimization techniques into the design of e - waste management systems, paving the way for more sustainable and cost - effective practices.

Keywords: Reverse Logistics, Mixed - Integer Linear Programming (MILP), Electronic Waste (e - waste).

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1. Introduction

Electronic waste (e - waste) has emerged as one of the fastest-growing waste streams worldwide, driven by rapid technological advancement, consumer demand, and shorter product lifecycles. According to the Global E - Waste Monitor 2020 published by the United Nations, approximately 53.6 million metric tons of e-waste were generated globally in 2019, a figure expected to escalate to 74 million metric tons by 2030 [1]. Alarmingly, only 17.4% of this waste is formally collected and recycled [1]. This substantial disparity between waste generation and proper treatment results in significant losses of valuable resources and contributes to serious environmental and health hazards due to toxic constituents such as lead, mercury, cadmium, and persistent organic pollutants [28].

In Vietnam, the situation is no less concerning. Data from the Ministry of Natural Resources and Environment indicate that e - waste generation increased from 89,000 tons in 2020 to an estimated 120,000 tons in 2023 [2]. Projections suggest that this volume could surpass 2.4 million tons by 2030 without effective policy interventions and system upgrades. Despite this surge, the formal recycling rate remains below 10%, implying that most e - waste is inadequately handled either left untreated, disposed of through environmentally harmful means, or processed by the informal sector [2]. This mismanagement not only exacerbates pollution but also leads to the loss of valuable materials such as gold, silver, palladium, cobalt, and lithium, which are typically embedded in electronic components.

Vietnam's current e - waste collection and recycling system is characterized by fragmentation and limited efficiency. Most households do not separate e-waste at source, resulting in it being mixed with general municipal solid waste. Discarded electronic devices are often sold to informal collectors, such as scrap dealers and street vendors. These materials are subsequently transported to informal recycling villages including Dong Mai (Hung Yen), Te Lo (Vinh Phuc), and Ngu Xa (Hanoi) where manual dismantling and rudimentary methods like open burning or acid baths are used to extract basic materials such as copper and plastics [3]. These processes are frequently conducted without personal protective equipment or environmental safeguards, posing significant health risks to workers and surrounding communities. On average, each informal facility processes between 1 and 10 tons of e-waste per day, yet high - value metals are often unrecovered and lost [3].

Complementing this informal system, Vietnam has approximately 15 officially licensed e - waste treatment facilities, each with a modest capacity ranging from 0.3 to 2.5 tons per day [4]. These formal facilities primarily focus on the recovery of common materials such as ferrous metals, lead, and plastic. However, they lack the advanced technological infrastructure required to efficiently recover precious and hazardous components. Consequently, a substantial portion of residual waste particularly materials containing heavy metals or toxic compounds that is incinerated, landfilled, or in some cases exported through unofficial channels, contributing to long - term environmental degradation. At present, all types of solid waste including e-waste are typically collected together from residential areas and transported to central gathering sites before being processed. (Fig.1).

These figures and realities highlight the urgent need to reform Vietnam's e - waste management system. As Extended Producer Responsibility (EPR) policies begin to take shape, developing optimized reverse logistics models, enhancing source separation, upgrading recycling technologies, and integrating the informal sector into formal systems will be essential for improving resource recovery efficiency, minimizing environmental damage, and advancing toward a sustainable circular economy.

The remainder of this paper is structured as follows. Sect. 2 presents related studies on reverse logistic network. Sect. 3 proposes new reverse waste collection network Sect. 4 entails MILP for reverse logistics design. Sect. 5 presents the computational results and discussions. Finally, conclusions and suggestions for future works are addressed in Sect. 6.

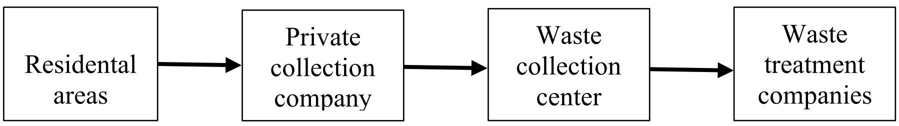

Figure 1. Current E - Waste Collection Process in Ho Chi Minh City.

2. Literature Review

Reverse logistics (RL) has long been recognized as a critical component of sustainable electronic waste (e - waste) management. Foundational studies by Fleischmann *et al.* [7] and Thierry *et al.* [8] defined RL as a structured process encompassing product return, disassembly, reuse, and recycling. Building on this foundation, subsequent research has developed various optimization models particularly mixed - integer linear programming (MILP) to design efficient RL networks aimed at minimizing costs, increasing resource recovery, and reducing environmental impact [9-11].

However, a review of the literature reveals several critical gaps that limit both the theoretical depth and practical applicability of existing models especially in the context of developing countries.

First, many studies focus narrowly on a single category of electronic products, such as mobile phones [12], personal computers [13], or printed circuit boards [14]. This narrow scope fails to reflect the heterogeneous nature of consumer e-waste in practice, which typically includes a wide variety of devices such as televisions, printers, washing machines, and refrigerators with diverse physical structures and material compositions. This limits the generalizability and real - world applicability of these models, particularly in emerging economies.

Second, most models are constructed under idealized assumptions stable operational conditions, complete infrastructure, and uniform processing capabilities. Real - world complexities, such as manual dismantling, improper source separation, and the presence of hazardous components like lithium batteries and CRT screens, are often excluded. For example, studies by Kara *et al.* [15] and Shevchenko *et al.* [16] developed MILP models for RL network design but did not incorporate the cost-intensive and technically challenging steps of disassembly or hazardous material separation.

Third, existing models frequently assume the presence of advanced, automated processing infrastructure, which is typically unavailable in low- and middle-income countries. For example, Alumur *et al.* [9] and Özceylan [10] base their models on highly mechanized systems, overlooking the technological and financial constraints that characterize many developing countries, such as Vietnam. Although Sajan *et al.* [18] proposed a more integrated framework encompassing collection, sorting, and treatment, it insufficiently addressed capacity limitations, investment risks, and outdated equipment that commonly hinder implementation.

Fourth, the informal sector, which plays a dominant role in e-waste collection and preprocessing across much of the developing world, is largely excluded from analytical models. Studies such as Eskandarpour *et al.* [11] and Kumar & Saini [17] focus solely on formal systems, thereby failing to capture the actual material flows and decision-making dynamics shaped by informal actors who, in countries like Vietnam, India, and Bangladesh, often handle a significant portion of e-waste.

These gaps highlight the need for a more context-sensitive approach tailored to the technological, economic, and operational realities of e - waste management in developing economies.

To address the identified limitations, this study proposes a reverse logistics model designed to handle diverse types of consumer electronic products, regardless of size or material complexity. Unlike previous models, it integrates key operations such as sorting, dismantling, and hazardous material separation within a single treatment facility, enhancing process efficiency. Furthermore, it incorporates a technological constraint variable to reflect the actual processing capacities of both formal and informal sectors. By aligning more closely with real - world conditions in developing countries, the model offers a practical, scalable framework for reverse logistics planning and supports policymakers in promoting circular economy strategies.

3. Analysis of Current Status Collection and the E-Waste Reverse Logistics Network

3.1. The Current Status E - Waste Collection

The formal e - waste sector in Vietnam remains hampered by outdated technology and limited capacity. Although around 15 licensed facilities exist, each can process only 0.5 – 3 tons per day using manual disassembly, basic sorting, and recovery of common metals. A few have small - scale printed circuit board (PCB) preprocessing lines, but none possess the advanced, large - scale equipment needed to extract precious metals or safely treat hazardous substances. As a result, recovery yields remain low and harmful byproducts are released.

Informal recyclers and scrap dealers from traditional craft villages such as Minh Khai and Te Lo to roadside collectors outcompete the formal sector by offering higher prices for e-waste and using rapid, low - cost methods. They burn cables or leach PCBs in acid to recover copper, aluminum, and iron, neglecting valuable metals, plastics, and microcomponents. These primitive techniques not only waste resources but also emit lead, mercury, cadmium, dioxins, and other toxins, posing severe environmental and human health risks.

Vietnam's overall e - waste recycling rate remains below 10% of the total generated volume. Informal processors recover roughly 75% of metal content from air conditioners, under 40% from refrigerators, about 30% from washing machines, and only 20% from televisions. The remainder is lost or improperly disposed, further burdening landfills and contaminating air, soil, and water.

Table 1: List of Products Required for Collection and Recycling (to be effective from 01 January 2022)

Discarded Product	Effective Date
Packaging (paper, plastic, metal, glass)	January 1, 2024
Batteries	
Lubricants	
Tires	
Electrical and electronic equipment (household appliances, IT devices, light bulbs, computers, solar panels)	January 1, 2025
End-of-life vehicles	January 1, 2027
Other packaging (to be decided by the Prime Minister)	

(Source: MONRE, 2021)

Regulatory gaps compound these technical and economic challenges. Although the Environmental Protection Law of 2020 introduced extended producer responsibility (EPR) and scheduled phased collection requirements (e - waste collection mandatory from January 1, 2025), implementing decrees remain vague, inconsistently applied, and lack enforcement mechanisms. Without clear targets, penalties, or incentives, consumers continue to favor informal channels, and formal facilities struggle to secure feedstock. These limitations underscore the need for a well - designed collection network, featuring strategically located centralized collection centers in areas with high volumes of electronic waste. These centers should be equipped to conduct initial sorting on - site and should incorporate incentive mechanisms to encourage voluntary public participation. By integrating modern technology and management systems, such a network could improve collection efficiency, lower operational costs, and maximize the recovery of reusable components and recyclable materials.

3.2. Types of Facilities in the Network

The types of facilities in the electronic waste (e - waste) recovery network are identified based on the principle of functional division according to the recycling value chain, aiming to optimize material flow, reduce costs, and minimize environmental impact. Wang *et al.* [19] pointed out that separating the collection and initial sorting at centralized stations helps reduce the volume of mixed waste sent to processing plants, thereby improving metal extraction efficiency and protecting high-tech equipment from contamination. Kaya *et al*. [20] emphasized the role of component storage facilities as a *"buffer"* for valuable parts, enabling flexible coordination of supply between processing plants and reuse markets, reducing waste, and maintaining a stable supply of raw materials for recycling manufacturers. Saputra *et al.* [6] demonstrated that establishing primary (raw material sales) and secondary (recycled product sales) markets not only creates economic incentives for collectors and businesses but also encourages stakeholder participation in the Extended Producer Responsibility (EPR) model.
The e - waste recovery model with five facilities centralized collection stations, processing plants, component storage, primary markets, and secondary markets is designed based on the multi - layer logistics principle to ensure recovery and sorting efficiency, enhance supply flexibility, and promote economic value from recycling. (Table 2) This model not only optimizes resource recovery and reduces operational costs but also enhances the effectiveness of EPR policy implementation in Vietnam, drawing on international best practices. The table below outlines the role and function of each facility in this model.

Table 2: Facility Types in the Proposed E - Waste Recovery Network

Facility Type	Function
Centralized Collection	Collect e - waste from residential areas and businesses; perform preliminary sorting.
Processing Plants	Disassemble, extract basic and precious metals, and treat hazardous substances.
Component Storage	Store usable parts for recycling or reuse.
Primary Market	Sell recovered components and metals to manufacturers or processors.
Secondary Market	Sell recycled products and reusable items to end consumers.

3.3 Main Activities in the E - Waste Reverse Logistics Network

E - waste recovery is an essential part of sustainable waste management, aiming to reduce environmental harm and reclaim valuable resources. According to studies such as Srivastava *et al.* [21] and Kaya *et al.* [22], the e - waste recovery network involves a series of closely connected activities, from collection to recycling as following:

- *Initial Collection:* This process begins when consumers bring electronic waste to centralized collection points (RCHs) or request home collection, often accompanied by incentive mechanisms. At RCHs, devices are received, undergo initial inspection, and are temporarily stored safely.
- *Logistics Transportation*: The devices are then transported from RCHs to processing plants (CPFs) and between other facilities in the network (warehouses, consumption markets). This activity needs to be optimized using technology to ensure efficiency and safety for the electronic waste.
- *Processing at the Manufaturer*: This is the central hub of the process, where electronic waste is sorted in detail using both manual and automated methods. Key activities here include inspection, diagnosing reusability, securely destroying data on storage devices, repairing and refurbishing functional products, disassembling and recovering valuable components, and separating hazardous or non - recyclable components for final disposal.
- *Warehouse Management:* Repaired products and recovered components are transported to warehouses (which could be RCHs or central warehouses). Here, they are received, sorted, organized, and inventory is managed before being dispatched for distribution to the market.

- *Redistribution and Final Disposal:* Refurbished products and reusable components from the warehouse are sold back into the secondary and primary markets. Recyclable materials like metals and plastics are also supplied to industries. As for the waste fraction that has no value or is hazardous and cannot be otherwise processed, it is transported to licensed facilities for safe disposal (landfilling or incineration).

3.4 Products Involved in the E - Waste Reverse Logistics Network

Against the backdrop of the rapidly increasing volume of electronic waste in Vietnam, a recovery system is established to collect and process these types of equipment when they reach the end of their lifespan or malfunction. The purpose is to transform them from a waste stream into valuable materials that can be recycled or reused, thereby contributing to the effective management of this specific waste flow. When a broken electronic device enters the processing procedure, the initial and crucial core activity is the disassembly and breakdown of its internal components. This process aims to separate the mixed electronic waste into more homogeneous material streams for subsequent processing stages.

After disassembly, electronic waste can be classified into main groups including: PCB (Printed Circuit Board), damaged parts, and mechanical parts, also known as reusable parts (like casings, frames, buttons...). From the damaged parts group, further sorting separates them into recyclable materials (such as Metal, Plastic) and other components that may be non - recyclable or contain hazardous materials (e.g., Batteries containing Cobalt, toxic materials like lead, cadmium, mercury...). (Fig 2.) This detailed classification is essential because different components of electronic waste contain both valuable precious metals that can be recovered and hazardous substances that require safe handling to ensure effective recycling, refurbishment, and disposal.

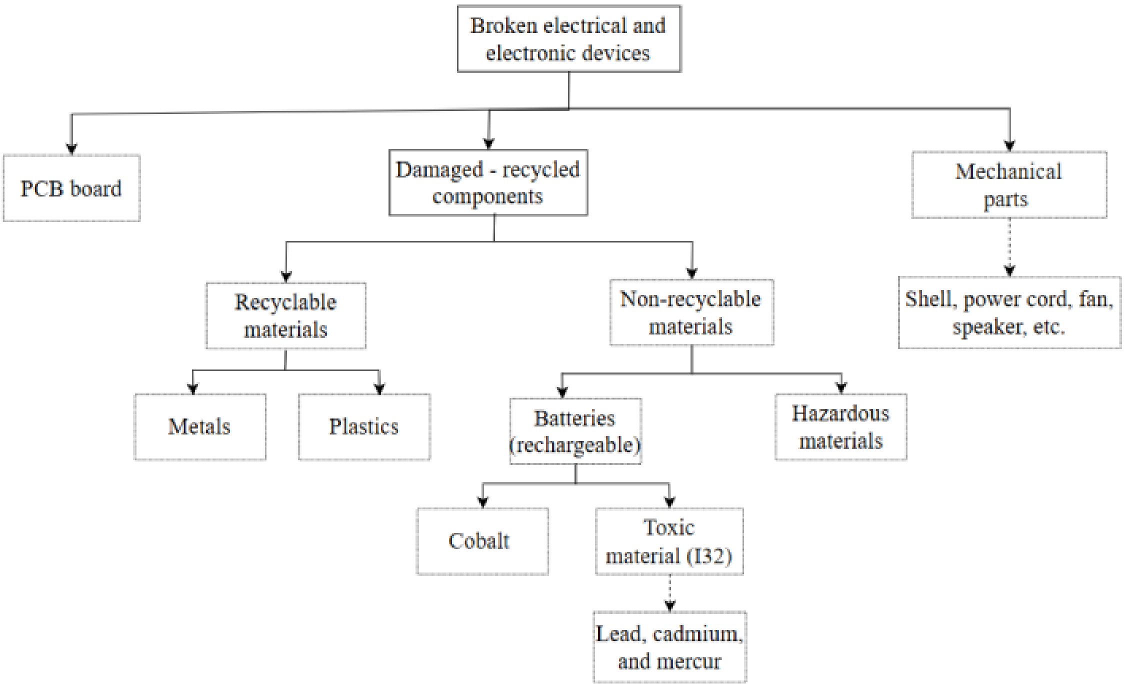

Figure 2. General process of dismantling electrical and electronic equipment.

Following the disassembly stage of end – of - life electronic and electrical equipment, detailed classification by material composition serves as a foundational step for downstream processing. This activity is carried out based on the constituent material properties and the requirements of the appropriate final processing method. As illustrated in detail in Figure 3. Recycling groups of parts when disassembling electronic - electrical equipment, the components after disassembly are systematically separated into four main groups based on recovery potential and characteristics: Plastic recycling group, Common metal recycling group, Precious metal recovery group, and Hazardous component group. This specific division into distinct groups is necessary because each type of material requires specialized recycling or disposal technology. This detailed grouping process not only contributes to optimizing the efficient recovery of high-value resources like precious metals and enhances the quality of secondary raw materials for the recycling industry, but also ensures that hazardous materials are tightly controlled and safely processed, preventing the risk of environmental contamination. (Fig.3). Therefore, recycling group classification, clearly shown in the diagram, is an essential stepping stone to ensure the entire electronic waste management system operates effectively from both an economic and environmental responsibility perspective.

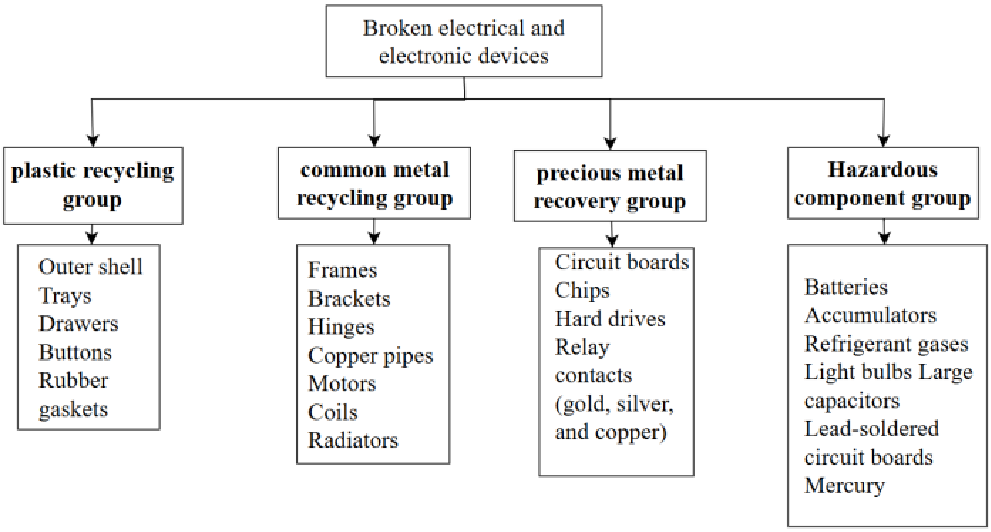

Figure 3. Recycling categories of components during the dismantling of electrical and electronic equipment

4. Mathematical model

The problem focuses on designing a reverse logistics network to collect, process, and recycle electronic waste from households and residential areas. The system comprises collection points within neighborhoods, a central processing facility, and storage warehouses for distributing recycled products. (Fig.4) The main objective is to optimize the locations and quantities of collection points, the processing capacity of the facility, and storage capabilities to minimize operating costs while maximizing profits from recycling and reusing components. A MILP model is employed to address the problem, optimizing costs to support effective and sustainable network design decisions.

To formulate the mathematical model, the assumptions are as follows:

- The supply of electronic waste is stable.
- Inventory costs at collection points and plants are considered negligible, with inventory costs only considered at the warehouse.
- Operating costs for collection points and warehouses are based on third - party labor, so these are treated as fixed costs for opening collection points and warehouses.
- The demand for purchasing reused products or components is less than or equal to the inventory from the previous week. If demand exceeds inventory, the unmet quantity will be included in the demand for the following week.

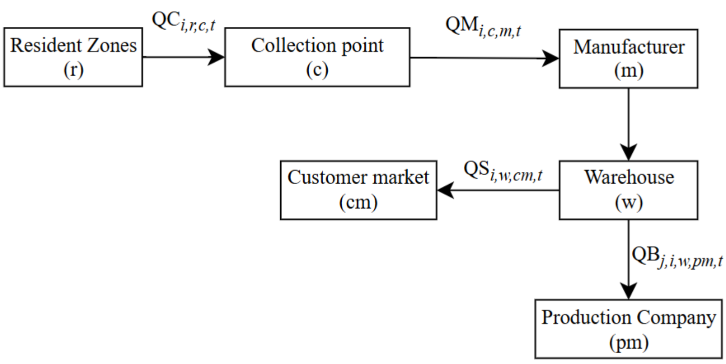

Figure 4. Reverse logistics network proposed

4.1 Notation Description of the Model

Before defining the objective function and constraints of the problem model, the related indices, parameters, and variables are presented as follows:

Indices:
i: Index of product i={1,2,…,I}
j: Index of component j={1,2,…,J}
r: Index of residential area r={1,2,…,R}
c: Index of collection point c={1,2,…,C}
m: Index of plant m={1,2,…,M}
w: Index of warehouse w={1,2,…,W}
cm: Index of customer market cm={1,2,…,CM}
pm: Index of primary market pm={1,2,…,PM}
k: Index of transportation vehicle k={1,2,…,K}
te: Index of technology te={1,2,…,TE}
t: Index of time period t={1,2,…,T}

Parameters
$N_{j,i}$: Quantity of component *j* in each product *i*
PRR_{te}: Repair success rate of products using technology *te*
PRC_{te}: Reuse rate of components disassembled from products by technology *te*
$DR_{i,r,t}$: Quantity of product *i* in residential area *r* at time period *t*
$DS_{i,cm,t}$: Demand for product *i* in secondary market *cm* at time period *t*
$DB_{i,j,pm,t}$: Demand for component *j* of products *i* supplier pm factory at time period *t*
$dc_{r,c}$, $dm_{c,m}$, $dw_{m,w}$, $ds_{w,cm}$, $db_{w,pm}$: Distance between utilities.
UT_k : Transportation cost per kilometer for vehicle *k*
UPI_{te} : Inspection and sorting cost per product using technology *te*
$UPR_{i,te}$: Repair cost per product *i* using technology *te*
$UPA_{i,te}$: Disassembly cost per product *i* using technology *te*
UCI_{te} : Inspection and sorting cost for reusable components by technology *te*
$UCD_{j,i}$: Disposal cost for component *j* of product *i*
UPS_i: Storage cost per product *i*
$UCS_{j,i}$: Storage cost per component *j* of product *i*
CAC_c : Capacity of collection point *c*
CAM_m : Capacity of facility *m*
CAW_w : Capacity of warehouse *w*
$QPI_{i,w,t-1}$: Quantity of product i inventory in warehouse *w* in the first period.
$QCI_{j,i,w,t-1}$: Quantity of component j of product i inventory in warehouse *w* in the first period.

Decision variables:

$$OTe_{te,m} = \begin{cases} 1 \text{ if facility m uses technology te} \\ 0 \quad \text{otherwise} \end{cases}$$

$QC_{i,r,c,t}$: Quantity of product *i* from residential area *r* to collection point *c* at time period *t*
$QM_{i,c,m,t}$: Quantity of product *i* from collection point *c* to manufacture m at time period *t*
$QS_{i,w,cm,t}$: Quantity of product *i* from warehouse *w* to secondary market cm at time period *t*
$QB_{j,i,w,pm,t}$: Quantity of component *j* of product *i* from warehouse *w* to factory supplier at time period *t*

4.2 Mathematical Model

This paper considers the minimum total cost of the reverse logistics network for electronic waste. Objective function are as follows:

Minimize Z = Transportation Cost between Area + Inspection and Sorting Cost + Repair Cost of Defective Products + Disassembly Cost of Not – Repaired Defective Products + Inspection and Sorting Cost for Reusable Components + Disposal Cost for Not – Reusable Components + Holding Cost of Repaired Products + Holding Cost of Reusable Components (1)

Transportation Cost from Residental area to Collection Center: (2)

$$\sum_{i=1}^{i=I}\sum_{t=1}^{t=T}\sum_{r=1}^{r=R}\sum_{c=1}^{c=C}\sum_{k=1}^{k=K} QC_{i,r,c,t} * dc_{r,c} * UT_k$$

Transportation Cost from Collection Point to Manufacturer: (3)

$$\sum_{i=1}^{i=I}\sum_{t=1}^{t=T}\sum_{m=1}^{m=M}\sum_{c=1}^{c=C}\sum_{k=1}^{k=K} QM_{i,c,m,t} * dm_{c,m} * UT_k$$

Transportation Cost from Manufacturer to Warehouse: (4)

$$\sum_{j=1}^{j=J}\sum_{i=1}^{i=I}\sum_{m=1}^{m=M}\sum_{w=1}^{w=W}\sum_{te=1}^{te=TE}\sum_{t=1}^{t=T}\sum_{k=1}^{k=K} (QM_{i,c,m,t} * PRR_{te} + QM_{i,c,m,t}\,(1 - PRR_{te}) * PRC_{te} * N_{j,i}) * dw_{m,w} * UT_k$$

Transportation Cost from Warehouse Customer Market: (5)

$$\sum_{i=1}^{i=I}\sum_{t=1}^{t=T}\sum_{cm=1}^{cm=CM}\sum_{w=1}^{w=W}\sum_{k=1}^{k=K} QS_{i,w,cm,t} * ds_{w,cm} * UT_k$$

Transportation Cost from Warehouse to Production Company: (6)

$$\sum_{j=1}^{j=J}\sum_{i=1}^{i=I}\sum_{pm=1}^{pm=PM}\sum_{w=1}^{w=W}\sum_{t=1}^{t=T}\sum_{k=1}^{k=K} QB_{j,i,w,pm,t} * db_{w,pm}$$

Inspection and Sorting Cost: (7)

$$\sum_{m=1}^{m=M}\sum_{i=1}^{i=I}\sum_{t=1}^{t=T}\sum_{c=1}^{c=C}\sum_{te=1}^{te=TE} QM_{i,c,m,t} * UPI_{te}$$

Repair Cost of Defective Products: (8)

$$\sum_{m=1}^{m=M}\sum_{i=1}^{i=I}\sum_{te=1}^{te=TE}\sum_{t=1}^{t=T} QM_{i,c,m,t} * PRR_{te} * UPR_{i,te}$$

Disassembly Cost of Not – Repaired Defective Products: (9)

$$\sum_{m=1}^{m=M}\sum_{i=1}^{i=I}\sum_{t=1}^{t=T}\sum_{te=1}^{te=TE} QM_{i,c,m,t}\,(1-PRR_{te}) * N_{j,i} * UPA_{i,te}$$

Inspection and Sorting Cost for Reusable Components: (10)

$$\sum_{m=1}^{m=M}\sum_{te=1}^{te=Te}\sum_{i=1}^{i=I}\sum_{j=1}^{j=J}\sum_{t=1}^{t=T} QM_{i,c,m,t}\,(1-PRR_{te}) * N_{j,i} * PRC_{te} * UCI_{te}$$

Disposal Cost for Not – Reusable Components: (11)

$$\sum_{j=1}^{j=J}\sum_{i=1}^{i=I}\sum_{m=1}^{m=M}\sum_{te=1}^{te=TE}\sum_{t=1}^{t=T} QM_{i,c,m,t}\,(1-PRR_{te}) * N_{j,i} * (1-PRC_{te}) * UCD_{j,i}$$

Holding Cost of Repaired Products: (12)

$$\sum_{t=1}^{t=t}\sum_{i=1}^{i=I}\left(\sum_{w=1}^{w=W} QPI_{i,w,t-1} + \sum_{c=1}^{c=C}\sum_{te=1}^{te=TE}\sum_{m=1}^{m=M} QM_{i,c,m,t} * PRR_{te} - \sum_{cm=1}^{cm=CM}\sum_{w=1}^{w=W} QS_{i,w,cm,t}\right) * UPS_i$$

Holding Cost of Reusable Components: (13)

$$\sum_{j=1}^{j=J}\sum_{i=1}^{i=I}\sum_{t=1}^{t=t}\left(\sum_{w=1}^{w=W} QCI_{j,i,w,t-1} + \sum_{c=1}^{c=C}\sum_{m=1}^{m=M}\sum_{te=1}^{te=TE} QM_{i,c,m,t} * (1-PRR_{te}) * PRC_{te} * N_{j,i} - \sum_{w=1}^{w=W}\sum_{pm=1}^{pm=PM} QB_{j,i,w,pm,t}\right) * UCS_{j,i}$$

In the above mathematical model, expression (1) represents the objective function, which aims to minimize the total cost of the reverse logistics network. This total cost comprises multiple components, as detailed in formulas (2) through (13), including: transportation costs between areas ,inspection and sorting costs, repair costs for defective products, disassembly costs for non-repairable defective products, inspection and sorting costs for reusable components, disposal costs for non-reusable components, and holding costs for both repaired products and reusable components. Among these, transportation costs from (2) to (6) cover multiple stages in the reverse logistics chain, such as transportation from residential areas to collection centers, from collection points to manufacturers, from manufacturers to warehouses, from warehouses to consumer markets, and from warehouses to production companies.

Constraints to:

$$\sum_{c=1}^{c=C} QC_{i,r,c,t} = DR_{i,r,t} \qquad \forall\, i,r,t \quad (14)$$

$$\sum_{m=1}^{m=M} QM_{i,c,m,t} = \sum_{r=1}^{r=R} QC_{i,r,c,t} \qquad \forall\, i,t,c \quad (15)$$

$$\sum_{w=1}^{w=W}\sum_{cm=1}^{cm=CM} QS_{i,w,cm,t} \le \sum_{c=1}^{c=C}\sum_{te=1}^{te=TE} QM_{i,c,m,t}\,(1-PRR_{te}) \qquad \forall i,t \ge 1 \quad (16)$$

$$\sum_{w=1}^{w=W} QS_{i,w,cm,t} = DS_{i,cm,t} \qquad \forall i,cm,t \ge 1 \quad (17)$$

$$\sum_{pm=1}^{pm=PM}\sum_{w=1}^{w=W} QB_{j,i,w,pm,t} \le \sum_{c=1}^{c=C}\sum_{m=1}^{m=M}\sum_{te=1}^{te=TE} QM_{i,c,m,t} * (1-PRR_{te}) * PRC_{te} * N_{j,i} \qquad \forall i,j,t \ge 1 \quad (18)$$

$$\sum_{w=1}^{w=W} QB_{j,i,w,pm,t} = DB_{j,i,pm,t} \qquad \forall pm,j,i,t \ge 1 \quad (19)$$

$$\sum_{te=1}^{TE=1} OT_{te,m} = 1 \qquad \forall m \quad (20)$$

$$\sum_{i=1}^{i=I}\sum_{r=1}^{r=R} QC_{i,r,c,t} \le CAC_c \qquad \forall c,t \quad (21)$$

$$\sum_{i=1}^{i=I}\sum_{c=1}^{c=C} QM_{i,c,m,t} \le CAM_m \qquad \forall m,t \quad (22)$$

$$\sum_{i=1}^{i=I}\sum_{te=1}^{te=TE}\sum_{m=1}^{m=M}\sum_{c=1}^{c=C}\left(\sum_{cm=1}^{cm=CM}(QPI_{i,w,t-1} + QM_{i,c,m,t} * PRR_{te} - QS_{i,m,cm,t}) + \sum_{j=1}^{j=J}\sum_{pm=1}^{pm=PM}(QCI_{j,i,w,t-1} + QM_{i,c,m,t}(1-PRR_{te}) * PRC_{te} * N_{j,i} - QB_{j,i,w,pm,t})\right) \leq CAW_w \quad \forall w,t \quad (23)$$

$$OT_{te,m} \in \{0,1\} \quad (24)$$

$$QC_{i,r,c,t}, QM_{i,c,m,t}, QS_{i,w,cm,t}, QB_{j,i,w,pm,t} \geq 0 \quad (25)$$

Constraints (14) to (19) represent the input and output quantities at each facility. Constraint (20) ensures that only one type of technology is invested in for each plant. Constraints (21) to (23) ensure that the quantity transferred to each facility at any given time does not exceed its processing capacity. Finally, constraints (24) and (25) define the nature of the decision variables used in the model.

5. Computational Results

To study the performance of the proposed model, the mathematical model is solved in CPLEX 22.1.1 on an Intel Core i7 1.8 GHz processor with 20 GB RAM in Windows 10. The model is tested with two test data sets. Through the test, we will provide insights about the model's effectiveness in different problem sizes.

A small dataset with a pre - established network consisting of 2 residential areas, 2 centralized collection points, 2 factories, 2 warehouses, 1 primary market, and 1 secondary market. There is one product, and this product has 2 types of components with quantities of 3 and 2, respectively.

The results of the optimization model suggest a single manufacturing facility should be established, rather than the initial plan for two, with the chosen technology corresponding to *"te=1"* at the first facility (Table 3). This outcome aligns with the objective of cost minimization given the specified input demand. By consolidating production into one facility equipped with the most suitable technology, the solution not only reduces operational expenses but also enhances the efficiency of resource utilization. Consequently, this streamlined approach can be more sustainable in the long term, providing a balanced response to both financial and operational constraints.

Table 3: *Results of Decision Variables open technology in manufacturer.*

$OTe_{te,m}$	Manufacture	
	m=1	m=2
te=1	1	0
te=2	0	0

The optimal results presented in Table 3 indicate that transportation costs are the highest component, accounting for 44358, compared to other costs such as component storage, reusable device storage, and in-plant processing. This highlights that transportation operations within the current e - waste recovery network remain a significant financial burden. These results are obtained by solving the proposed mathematical model in Section IV for the e - waste recovery operation using the CPLEX solver. The total cost of the recovery network is calculated to be 48814, which is considered reasonable for this case study. These results provide valuable insights for adjusting network management strategies, particularly by focusing on optimizing transportation routes, improving operational efficiency, and reducing overall costs.

The transition to a circular economy in Vietnam, coupled with pressing needs for cost optimization and environmental protection, finds a powerful catalyst in the establishment and effective operation of specialized electronic waste (e - waste) collection networks. These networks offer a holistic suite of benefits crucial for the nation's sustainable development.

A primary advantage lies in significant cost reduction and economic value creation. With national expenditure on municipal solid waste (MSW) treatment exceeding VND 14,300 trillion annually (0.23% of 2023 GDP), the strategic separation of e - waste at source can drastically cut these costs by reducing the volume and toxicity of waste requiring expensive processing. This not only saves public funds but also opens avenues for revenue generation. E - waste, often discarded, is rich in recoverable materials like metals and plastics. Specialized recycling can transform this *"waste"* into valuable resources, fostering new industries, creating jobs, and lessening reliance on finite natural resources. The increasing costs of conventional waste disposal, exemplified by Ho Chi Minh City's upcoming MSW treatment fee of VND 420.45/kg (from June 1, 2025), further solidify the economic case for dedicated e - waste recovery systems.

Beyond direct financial gains, these networks deliver critical environmental improvements. By diverting e - waste from the general waste stream, pressure on landfills is reduced, the operational life of treatment facilities is extended, and the release of hazardous substances like leachate is minimized. This targeted approach is fundamental to safeguarding Vietnam's natural environment. Furthermore, such initiatives are instrumental in driving corporate responsibility and enhancing systemic efficiency. Extended Producer Responsibility (EPR) regulations, alongside the clear economic upsides, motivate businesses to invest in and integrate e - waste collection into their reverse logistics. This not only ensures compliance but also optimizes material flows, reduces resource wastage, and bolsters corporate image and market competitiveness.

In conclusion, a specialized e-waste collection network is not merely a waste management strategy; it is a multifaceted approach that underpins economic prudence, environmental stewardship, and the advancement of a robust circular economy for Vietnam.

6. Conclusion and Future Research

This study successfully developed a Mixed - Integer Linear Programming (MILP) model for designing a reverse logistics network dedicated to the collection, sorting, dismantling, and treatment of waste electrical and electronic equipment (WEEE), particularly in the context of developing countries such as Vietnam. The proposed model explicitly integrates key operational stages including source separation, manual disassembly, and hazardous waste segregation into the network structure. Furthermore, it incorporates real - world technological limitations of both formal and informal treatment facilities, ensuring practical feasibility.

Simulation results based on empirical data demonstrate that the model effectively minimizes total operating costs, optimizes the location of collection and treatment centers, and increases the recovery rate of valuable materials such as copper, aluminium, gold, and engineering plastics. The findings also reveal that consolidating treatment operations within a single facility yields greater cost - efficiency compared to distributed models.

In terms of practical application, this model serves as a useful planning tool for local environmental departments, recycling firms, and urban waste management agencies seeking to implement province - level or interprovincial reverse logistics systems. For the informal sector which currently handles over 70% of WEEE in Vietnam the model provides a foundation for integrating them into formal networks through transfer stations or public – private partnerships.

From a policy perspective, the study highlights the need for regulatory bodies to design cost - sharing mechanisms among producers, consumers, and the public sector via Extended Producer Responsibility (EPR) policies. It also advocates for incentives to invest in clean processing technologies and the development of unified national standards for e - waste classification to support future automation.

Future research should focus on implementing and validating the proposed MILP model using real-world data collected from urban electronic waste treatment centers in Vietnam. In addition, a sensitivity analysis should be conducted to evaluate the model's responsiveness to changes in key parameters such as facility capacity, transportation costs, and recovery rates. To enhance the practical applicability of the reverse logistics network, future studies should also consider uncertainties related to demand from residential areas and secondary markets for recovered products/components, as well as CO_2 emissions generated during the treatment of different components. This approach can help reduce the number of discarded parts, encourage reuse within a new product lifecycle, and contribute to environmental protection goals. These factors will be validated using empirical data gathered from urban e-waste processing centers, thereby clarifying the feasibility of the proposed reverse logistics model.

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