

REVERSE LOGISTICS MODELING CONSIDERING ENVIRONMENTAL AND MANUFACTURING COSTS: A CASE STUDY OF BATTERY RECYCLING IN INDONESIA

Ilyas Masudin^{1*}, Thomy E. Saputro¹, Genial Arasy¹, Ferry Jie²

¹*Department of Industrial Engineering, University of Muhammadiyah Malang, Jl. Raya Tlogomas
246 Malang, 65144, Indonesia*

²*School of Business & Law, Edith Cowan University, 270 Joondalup Dr, Joondalup Westren Australia,
6027, Australia*

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ABSTRACT

This article models a reverse logistics network for battery recycling with consideration of environmental and manufacturing costs. The model is developed for a reverse flow multi-echelon supply chain, from end customers to the remanufacturing process. Linear programming is used to formulate mathematical models and LINGO[®] is applied to solve the problem of determining optimal orders for and sales of recycled batteries, lead alloy and plastics, as well as the optimal level of safety stock (service level) for the recycling centers along the reverse logistics network. The number of battery orders from unused battery collectors, and the sales of lead alloy and plastics to the remanufacturing process considering transportation, environmental cost, disassembly cost and inventory costs, are found optimally in different periods. The study also indicates that there is a correlation between the associated costs and inventory decisions and total profit in recycling centers.

Keywords: Recycling; Remanufacturing; Reverse logistics

1. INTRODUCTION

Reverse logistics (RL), which refers to a series of activities starting from the level of customer collection of products and ending with product remanufacturing processes, has received much attention recently in term of approaches and network models (Sarkis, 2001; Soto Zuluaga, 2005; Wang, 2015). Reverse logistics has become an issue of increased concern in environmental studies since the operation of the manufacturing process, particularly for hazardous materials, impacts negatively on all the parties in a supply chain if it is not appropriately organized. Employing good logistics management throughout the material flow, with the involvement of planning, managing and controlling the flow of waste until its disposal, can alleviate the risk of hazardous material. In the outbound side of green supply chain management, reverse logistics, or environmental distribution, is an approach to improve firms' environmental performance (Rao, 2002).

The optimization model for dealing with transportation and routing problems by controlling the risk of hazardous waste from the perspective of reverse distribution planning has developed rapidly. However, most of the reverse distribution planning models only focus on production planning (Guide Jr, 2000; Park, 2005). Regardless of such focus, this study exclusively deals with

*Corresponding author's email: masudin@umm.ac.id, Tel. +62-341-464318, Fax. +62-341-460435
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the production planning and inventory control which are integrated into the developed model. Products such as batteries, which contain hazardous material, can have a negative effect on the environment (Kusrini et al., 2015). This study develops a linear programming model for multi-period RL in order to determine the optimal number of batteries that should be produced and the number which should be stored as inventory. The objective of the proposed model is to minimize total logistics cost, including those of purchase, inventory and transportation, with respect to the environmental risk cost. The study develops RL models for batteries in a multi-echelon distribution system with consideration of environmental manufacturing costs, from the point of supply to the point of collection and then delivery to the remanufacturing point.

2. REVERSE LOGISTICS

De Brito and Dekker (2004) divided RL activities into two parties which are involved in the process of moving products back from a supply chain, namely the returner and receiver. The returner party is involved with product recall or value recovery, which are actively related to the consumers of a product, while the purpose of the receiver party is to make a profit and social pressure. The activities of the returner party include reselling, redistributing, reusing, reprocessing and recovering value.

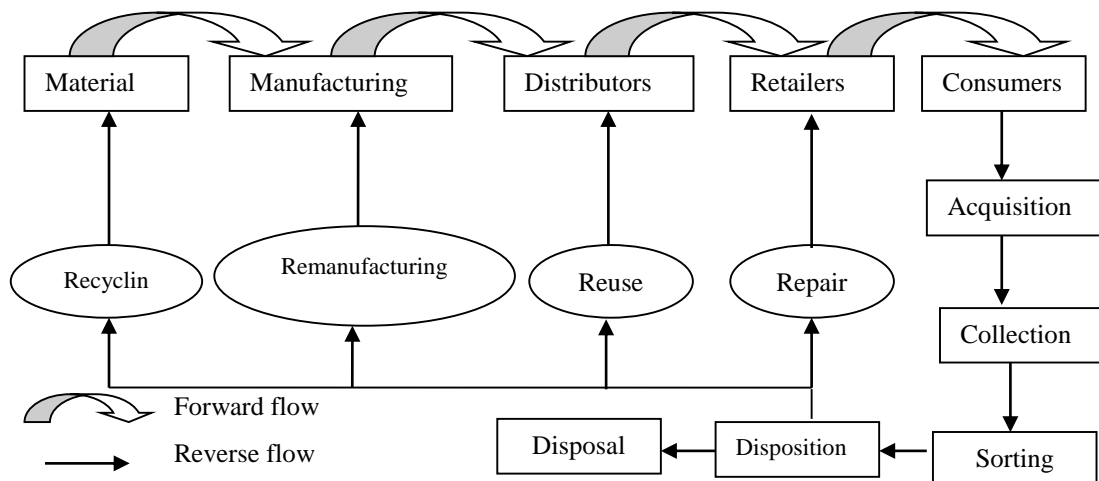


Figure 1 Basic process of forward and RL

Figure 1 shows the basic processes of forward and RL based on a previous RL study by Guide et al. (2003). The used products are collected by the secondary market after acquisition activities and then sorted into the next processes.

2.1. Revenue from RL

Returned products involve a variety of costs in the remanufacturing processes. Manufacturers often prepare a particular supply chain network to manage their returned products, developing or renting facilities at downstream levels, and involving dealers, collectors or third parties, who undertake acquisition, sorting or dropping off at the returned product centres, before shipping to manufacturers. According to Thomopoulos (2016), there are five sources of revenue for the manufacturer of returned products, namely refurbishment, remanufacturing, redistribution, and discard.

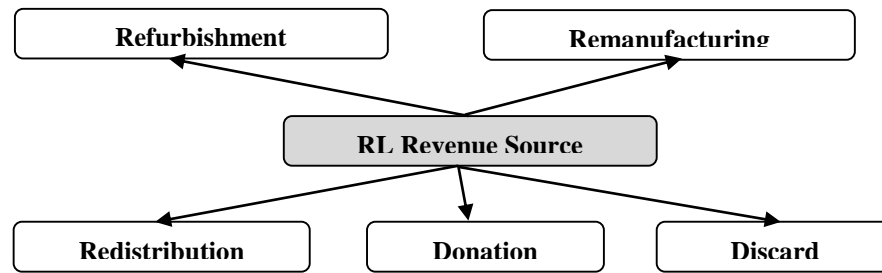


Figure 2 Sources of revenue from returned products

The main objective of remanufacturing activities in RL is to restore the quality of returned products to that which is conformable. There are various reasons for firms to conduct remanufacturing processes. First, the market pressure: customers are currently becoming more environmentally conscious in eco-manufacturing decision-making issues. This therefore creates significant pressures for the manufacturer to implement RL or green manufacturing, as well as enhancing its corporate image and gaining competitive advantage. The second reason is related to government regulations. In some countries, especially in developed ones such as the U.S and European countries, legislation forces manufacturers to take responsibility for their products after use by customers and for product disposal. Third, the financial perspective is the main point for companies to establish eco-remanufacturing processes. According to Thierry et al. (1995), the cost of remanufacturing processes is equivalent to 40–60% of that of manufacturing a new product, but it takes only 20% of the effort.

2.2. Recycling Network

The recycling network in RL concerns the recovery of low-value materials from items thrown away, which are processed as materials along the forward-flow of the supply chain. Generally, the recycling network concerns strategic decisions involving the number of facilities, facility locations, facility capacity and size, and market acquisition. Furthermore, it deals with the selection of appropriate methods or approaches to solve the recycling network problem. Study of RL with regard to recycled batteries has been growing recently due to economic reasons and environmental considerations (Efendigil, Önüt, & Kongar, 2008). Most approaches to the study of the recycling network can be classified into two categories, namely heuristics optimization and analytical qualitative exploration. For instance, Schweiger and Sahamie (2013) combined the facility location problem and Tabu Search method to develop their RL network for recycled paper manufacturers. Indrianti and Rustikasari (2010) proposed a reverse logistic model for the production planning of battery recycling using linear programming.

2.3. Methods and Approaches

Dowlatshahi (2000) categorized RL study into three groups. The first group focuses on remanufacturing activities and their influences on remanufacturing of the life cycle (Raupp et al., 2015). The second group of RL literature encompasses quantitative models. Some related studies which adopt quantitative models, such as that of (Kaya & Urek, 2016), have developed RL models and techniques, namely the cost-based model and linear programming, in order to improve RL activities, particularly for remanufacturing operations and product failure rate reduction. Qualitative studies have also been conducted using Kansei engineering and the Kano model (Hartono, Santoso, & Prayogo, 2017). The third group of RL literature discusses distribution/transportation (Zhou & Zhou, 2015) and warehousing (Ko & Evans, 2007).

3. RL NETWORK AND MATHEMATICAL MODEL

The RL battery network and the development of the mathematical model are introduced as follow.

3.1. Network Diagram for the Battery Recycling System

According to the model, we center on various parties involved in the study, namely the supplier, factory, distribution center, end user, collection center, recycling center, and disposal center. The supplier is the company supplying raw materials for battery production to the factory, while the factory is the company engaged in battery manufacturing. The distribution center is responsible for distributing batteries to the end user, the end user being the party utilizing the batteries for a particular need. The disposal center deals with the final disposal of the battery and is responsible for receiving the disposed or unused batteries. The collection center is the party which collects used batteries; this collected material is recycled at the recycling centre, and the recycling process will yield lead alloy and plastic, which are needed by the factory as raw material for battery production.

Figure 3 illustrates the model introduced into the RL of unused batteries. This study takes into account environmental value and aims to determine the optimal solution for the quantity of unused batteries to be purchased and the sale quantity of lead alloy and plastic. Therefore, we expect to achieve the maximum profit.

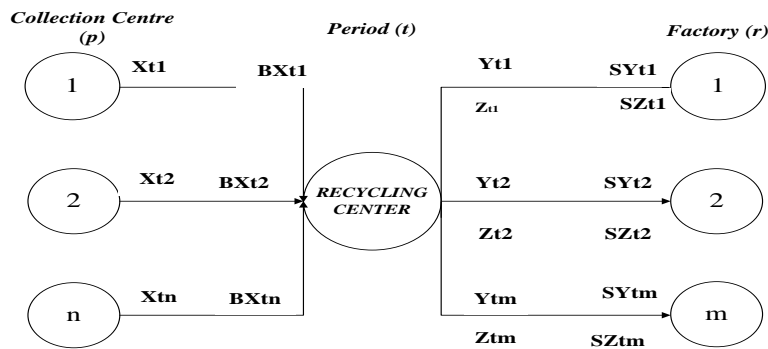


Figure 3 RL structure

The quantity of unused batteries purchased by the recycling center from the collection center (p) in a particular period (t) is denoted by X_{pt} . BX_{tp} is the purchase cost of the unused batteries from the collection center (p) undertaken by the recycling center in a particular period (t). The unused batteries will be dismantled in order to obtain lead alloy (Y) and plastic (Z), which is sold to the factory (r). Y_{rt} is the sale quantity of lead alloy by the recycling center to factory (r) in a particular period (t), with sale price SY_{tr} . The sales quantity of plastic is denoted by Z_{rt} at the price of SZ_{rt} . The cost of ownership applied to the recycling center includes the battery holding costs per unit (HX_t), the holding cost of lead alloy per unit (HY_t), the holding cost of plastic per unit (HZ_t), the cost of recycling (COD) and transportation costs (CT). Since the load capacities of the vehicles (K) for lead alloy (Y) and plastic (Z) are different, transportation costs, including fixed cost (F) and variable cost (V), are clearly also different. Moreover, the costs to be paid as the result of the environmental impact which emerges due to the fuel emissions during the transportation process (E_e, E_a) and the abiotic waste during the recycling process (E_s) are also taken into account. The decision variables involve the quantity of unused batteries to be purchased (X_{tq}), the sales quantity of lead alloy (Y_{rt}) and plastic (Z_{rt}), the inventory of the unused batteries (XI_t), the inventory of lead alloy (YI_t), and the inventory of plastic (ZI_t). Indrianti and Rustikasari (2010) proposed a single period linear programming model for the RL of unused batteries. The model incorporated the cost to the environment, with the objective function being to optimize total purchase and sale costs. The proposed model in this study will

be more comprehensive than that of Indrianti and Rustikasari (2010), since inventory cost is also incorporated together with other costs. In addition, this study also enhances the planning horizon of the RL problem into a multi-period model. It is evident that the multi-period model can tackle the problem more adequately rather than the single-period one.

3.2. Notation

Indices;

- t : Index for period; $t = 1, 2, \dots, T$
 p : Index for collection center; $p = 1, 2, \dots, n$
 r : Index for factory; $r = 1, 2, \dots, m$

Decision variables;

- X_{pt} : Quantity of batteries (X) purchased from the collection center (p) by the recycling centre at a certain time (t) (kg)
 Y_{rt} : Quantity of lead alloy (Y) sold by the recycling center to the factory (r) at a certain time (t) (kg)
 Z_{rt} : Quantity of plastic (Z) sold by the recycling center to the factory (r) at a certain time (t) (kg)
 XI_t : Quantity of batteries (X) stored at a certain time (t) (kg)
 YI_t : Quantity of lead alloy (Y) stored at a certain time (t) (kg)
 ZI_t : Quantity of plastic (Z) stored at a certain time (t) (kg)

Parameters;

- BX_{pt} : Purchase price of batteries (X) from the collection center (p) to the recycling center at a certain time (t) (\$/kg)
 SY_{rt} : Selling price of lead alloy (Y) from the recycling center to the factory (r) at a certain time (t) (\$/kg)
 SZ_{rt} : Selling price of plastic (Z) from the recycling center to the factory (r) at a certain time (t) (\$/kg)
 SSX : Safety stock for batteries (kg)
 SSY : Safety stock for lead alloy (kg)
 SSZ : Safety stock for plastic (kg)
 HX_t : Holding cost of the batteries (X) at the recycling center at a certain time (t) (\$/kg)
 HY_t : Holding cost of lead alloy (Y) at the recycling center at a certain time (t) (\$/kg)
 HZ_t : Holding cost of plastic (Z) at the recycling center at a certain time (t) (\$/kg)
 D : Disassembly cost of batteries (X) at the recycling center (\$/kg)
 FX : Fixed transportation cost for batteries (\$/travel)
 FY : Fixed transportation cost for lead alloy (\$/travel)
 FZ : Fixed transportation cost for plastic (\$/travel)
 VX : Variable transportation cost for batteries (\$/kg)
 VY : Variable transportation cost for lead alloy (\$/kg)
 VZ : Variable transportation cost for plastic (\$/kg)
 KX : Vehicle capacity for batteries (X) from the collection center (p) to recycling center (\$/kg)
 KY : Vehicle capacity for shipping lead alloy (Y) from the recycling center to factory (r) (kg)
 KZ : Vehicle capacity for shipping plastic (Z) from the recycling center to factory (r) (kg)
 LX_p : Distance from collection center (p) to recycling center (km)
 LY_r : Distance from recycling center to factory (r) for lead alloy (km)
 LZ_r : Distance from recycling center to factory (r) for plastics (km)
 A : Distance covered per litre of fuel (km/litre)
 IY_{max} : Maximum storage capacity for lead alloy (kg)

- $I_{Z_{max}}$: Maximum storage capacity for plastics (kg)
 $I_{X_{max}}$: Maximum storage capacity for batteries (kg)
 QX_t : Quantity of batteries (X) available at the collection center (p) at a certain time (t)
 QY_{rt} : Lead alloy demand (Y) by the factory (r) at a certain time (t) (kg)
 QZ_{rt} : Plastic demand (Z) by the factory (r) at a certain time (t) (kg)
 PY : Percentage of lead alloy (Y) resulting from the disassembly per kg of batteries (%)
 PZ : Percentage of plastic (Z) resulting from the disassembly per kg of batteries (%)
 E_e : Cost of fuel emissions (\$/kg)
 E_a : Fuel Index (\$/kg)
 E_s : Value of abiotic stock resource for lead alloy waste (\$/kg)
 RY : Total revenue from lead alloy (\$)
 RZ : Total revenue from plastic (\$)
 COP : Total purchase cost (\$)
 COD : Total recycling cost (\$)
 COH : Total holding cost of the batteries, lead alloy and plastics (\$)
 CTX : Total transportation cost of batteries (\$)
 CTY : Total transportation cost of lead alloy (\$)
 CTZ : Total transportation cost of plastic (\$)
 COE : Total cost of environmental impact (\$)

Objective function;

Max profit = Total revenue – Total Cost

$$\text{Max } Z = (RY + RZ) - (COP + COD + COH + CTX + CTY + CTZ + COE)$$

$$\begin{aligned} \text{Max } Z = & \left[\sum_{t=1}^T \sum_{r=1}^m Y_{rt} \cdot SY_{rt} + \sum_{t=1}^T \sum_{r=1}^m Z_{rt} \cdot SZ_{rt} \right] - \left[\sum_{t=1}^T \sum_{p=1}^n X_{pt} \cdot BX_{pt} + \sum_{t=1}^T \sum_{p=1}^n D \cdot X_{pt} + \right. \\ & \left. \left(\sum_{t=1}^T XI_t \cdot HX_t + \sum_{t=1}^T ZI_t \cdot HZ_t \right) + \sum_{t=1}^T \sum_{p=1}^n \left(\frac{X_{tp}}{KX} \cdot FX + VX \cdot X_{tp} \right) + \sum_{t=1}^T \sum_{r=1}^m \left(\frac{Y_{rt}}{KY} \cdot FY + \right. \right. \\ & \left. \left. VY \cdot Y_{rt} \right) + \sum_{t=1}^T \sum_{r=1}^m \left(\frac{Z_{rt}}{KZ} \cdot FZ + VZ \cdot Z_{rt} \right) + \left(\frac{2}{A} \right) (E_e + E_a) \left(\sum_{t=1}^T \sum_{r=1}^m \frac{Y_{rt}}{KY} \cdot LY_r + \sum_{t=1}^T \sum_{r=1}^m \frac{Z_{rt}}{KZ} \cdot LZ_r + \right. \right. \\ & \left. \left. \sum_{t=1}^T \sum_{p=1}^n \frac{X_{pt}}{KX} \cdot LX_p \right) + E_s \sum_{t=1}^T \sum_{p=1}^n X_{pt} \right] \quad (1) \end{aligned}$$

where:

$$RY = \sum_{t=1}^T \sum_{r=1}^m Y_{rt} \cdot SY_{rt} \quad (1.1)$$

$$RZ = \sum_{t=1}^T \sum_{r=1}^m Z_{rt} \cdot SZ_{rt} \quad (1.2)$$

$$COP = \sum_{t=1}^T \sum_{p=1}^n X_{pt} \cdot BX_{pt} \quad (1.3)$$

$$COD = \sum_{t=1}^T \sum_{p=1}^n D \cdot X_{pt} \quad (1.4)$$

$$COH = \sum_{t=1}^T XI_t \cdot HX_t + \sum_{t=1}^T ZI_t \cdot HZ_t \quad (1.5)$$

$$CTX = \sum_{t=1}^T \sum_{p=1}^n \frac{X_{tp}}{KX} \cdot FX + VX \cdot X_{tp} \quad (1.6)$$

$$CTY = \sum_{t=1}^T \sum_{r=1}^m \frac{Y_{rt}}{KY} \cdot FY + VY \cdot Y_{rt} \quad (1.7)$$

$$CTZ = \sum_{t=1}^T \sum_{r=1}^m \frac{Z_{rt}}{KZ} \cdot FZ + VZ \cdot Z_{rt} \quad (1.8)$$

$$\begin{aligned} COE = & \left(\frac{2}{A} \right) (E_e + E_a) \left(\sum_{t=1}^T \sum_{r=1}^m \frac{Y_{rt}}{KY} \cdot LY_r + \sum_{t=1}^T \sum_{r=1}^m \frac{Z_{rt}}{KZ} \cdot LZ_r + \sum_{t=1}^T \sum_{p=1}^n \frac{X_{pt}}{KX} \cdot LX_p \right) + \\ & E_s \sum_{t=1}^T \sum_{p=1}^n X_{pt} \quad (1.9) \end{aligned}$$

Constraints;

$$\sum_{r=1}^m Y_{tr} = \sum_{p=1}^n (X_{pt} \cdot PY) \quad (2)$$

$$\sum_{r=1}^m Z_{tr} = \sum_{p=1}^n (X_{pt} \cdot PZ) \quad (3)$$

$$\sum_{t=1}^T \sum_{p=1}^n X_{pt} + XI_{t-1} - XI_t \leq \frac{QY_{rt}}{PY} + \frac{QZ_{rt}}{PZ} \quad (4)$$

$$\sum_{t=1}^T \sum_{r=1}^m Y_{rt} + YI_{t-1} - YI_t \leq QY_r \tag{5}$$

$$\sum_{t=1}^T \sum_{r=1}^m Z_{rt} + ZI_{t-1} - ZI_t \leq QZ_r \tag{6}$$

$$SSX \leq XI_t \leq IXmax \tag{7}$$

$$SSY \leq YI_t \leq IYmax \tag{8}$$

$$SSZ \leq ZI_t \leq IZmax \tag{9}$$

$$X_{pt} \leq QX_{pt} \tag{10}$$

$$Y_{rt} \leq QY_{pt} \tag{11}$$

$$Z_{rt} \leq QZ_{rt} \tag{12}$$

$$X_{pt}, Y_{rt}, Z_{rt}, XI_t, YI_t, ZI_t, \forall t, p, r \geq 0 \quad (\text{Non negativity}) \tag{13}$$

According to Equation 1, the objective function is constructed to maximize total profit. The components of total cost are detailed in Equations 1.1–1.9 with respect to purchase cost, holding cost, transportation cost, recycling cost and environmental impact cost. Some constraints exist with the particular conditions, so demand, supply and inventory must be configured properly. Constraints (2) and (3) have the aim of balancing the supply and demand of lead alloy and plastic, respectively. Constraints (4), (5) and (6) configure simultaneously between inventories and recycling, so that the quantity of batteries, lead alloy and plastic produced for both do not exceed demand. Constraints (7), (8) and (9) ensure that the inventory can be controlled in a bound amount within a safety stock and maximum storage capacity. Constraints (10), (11) and (12) ensure that the quantity of batteries, lead alloy and plastic produced by the recycling process is lower than demand.

4. NUMERICAL RESULTS

In the study, six collection centers, one recycling center, four lead alloy manufacturers and five plastics manufacturers are involved in the RL network model and LINGO® is used to solve the RL problem. The optimal solution results of the proposed RL are shown in Table 1.

Table 2 shows that the decision to purchase recycled batteries by the recycling center is from collection centre 2, collection centre 3, collection centre 4 and collection centre 5, with purchase quantity varying in each period, while collection centre 1 and collection centre 6 were not selected as suppliers.

The optimal solutions for recycled lead alloy and plastics supply for the factories are shown in Table 3, which indicates that total supply of lead alloy and plastics varied in each period and between factories. The inventory of recycled batteries, lead alloy and plastics is shown in table 4, which indicates that optimal storage for recycled batteries, lead and plastic did not change in each period of time.

4.1. Sensitivity Analysis

Sensitivity analysis was conducted on several parameter changes, such as transportation and disassembly costs, to determine the level of influences on changes in profit and service level that influence the safety stock of recycled batteries, lead alloy and plastics, as well as changes in their holding costs.

$$\text{Profit changes} = \frac{z}{\text{reduction interval}} \tag{14}$$

where z is the average value of the reduction in profit $((Y_n)-(Y_{n+1}))$, and *reduction interval* is equal to difference in value of parameter change.

Table 1 Optimal recycling center battery orders

| Recycling centre purchase of batteries (kg) | | | | | |
|---|----------------|---------------------|----------------|---------------------|----------------|
| Collection centre 1 | | Collection centre 2 | | Collection centre 3 | |
| Availability | Order decision | Availability | Order decision | Availability | Order decision |
| 10,500 | 0 | 10,500 | 10,500 | 9,500 | 9,500 |
| 9,900 | 0 | 9,000 | 9,000 | 9,200 | 6,254 |
| 10,200 | 0 | 10,800 | 4,394 | 9,400 | 9,400 |
| 10,000 | 0 | 10,200 | 8,148 | 9,800 | 9,800 |
| Collection centre 4 | | Collection centre 5 | | Collection centre 6 | |
| Availability | Order decision | Availability | Order decision | Availability | Order decision |
| 9,000 | 9,000 | 10,800 | 5,251.9 | 5,000 | 0 |
| 9,500 | 9,500 | 10,500 | 10,500 | 6,000 | 0 |
| 8,500 | 8,500 | 10,200 | 10,200 | 5,200 | 0 |
| 9,000 | 9,000 | 11,000 | 11,000 | 5,000 | 0 |

Table 2 Demand vs. supply of lead alloy and plastics

| Optimal supply of lead alloy (kg) | | | | | | | |
|-----------------------------------|--------|-----------|--------|-----------|--------|-----------|--------|
| Factory 1 | | Factory 2 | | Factory 3 | | Factory 4 | |
| Demand | Supply | Demand | Supply | Demand | Supply | Demand | Supply |
| 12,000 | 12,000 | 9,000 | 3,551 | 13,000 | 0 | 5,000 | 5,000 |
| 15,000 | 15,000 | 8,000 | 4,314 | 10,000 | 0 | 2,000 | 2,000 |
| 14,500 | 14,500 | 5,000 | 9,96.6 | 8,000 | 0 | 4,000 | 4,000 |
| 14,000 | 14,000 | 10,000 | 5,769 | 8,000 | 0 | 3,000 | 3,000 |

| Optimal supply of plastics (kg) | | | | | | | | | | |
|---------------------------------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|
| t | Factory 1 | | Factory 2 | | Factory 3 | | Factory 4 | | Factory 5 | |
| | Demand | Supply | Demand | Supply | Demand | Supply | Demand | Supply | Demand | Supply |
| 1 | 2,000 | 2,000 | 1,000 | 1,000 | 5,000 | 5,000 | 3,000 | 3,000 | 2,000 | 303 |
| 2 | 2,500 | 2,500 | 1,500 | 1,500 | 6,000 | 6,000 | 2,000 | 1,723 | 1,500 | 0 |
| 3 | 2,000 | 2,000 | 2,000 | 2,000 | 5,000 | 5,000 | 2,000 | 1,723 | 1,500 | 0 |
| 4 | 2,700 | 2,700 | 1,800 | 1,800 | 6,000 | 6,000 | 2,000 | 2,000 | 1,800 | 23.13 |

Table 3 Optimal storage solution

| Battery storage (XI)(kg) | Lead alloy storage (YI)(kg) | Plastic storage (ZI)(kg) |
|--------------------------|-----------------------------|--------------------------|
| 900 | 600 | 600 |
| 900 | 600 | 600 |
| 900 | 600 | 600 |
| 900 | 600 | 600 |

4.2. Transportation Cost and Disassembly Cost vs. Profit

Discussion of the tradeoffs between the transportation costs and profit of firms has been made previously by Thisse and Perreur (1977) in order to understand the point of maximum profit and minimum total transportation costs. The findings of their study are in line with the results of this research, showing that there is no change in the decision variables for the purchase quantity of unused batteries, the sales quantity of lead alloy and plastic, and the inventory of unused batteries, lead alloy and plastic, as the consequences of the change in transportation costs. The change has an effect by reducing total profit by 2.68% on average, along with the increase in fixed transportation costs.

There is no change in the decision variables for the purchase quantity of unused batteries, or the sales quantity of lead alloy and plastic, as consequences of the increase in recycling costs.

Meanwhile, the change in recycling costs does not affect the inventory of unused batteries, lead alloy or plastic. The change in recycling costs reduces total profit by 64.36% on average, along with the increase in recycling costs (see Figure 4b).

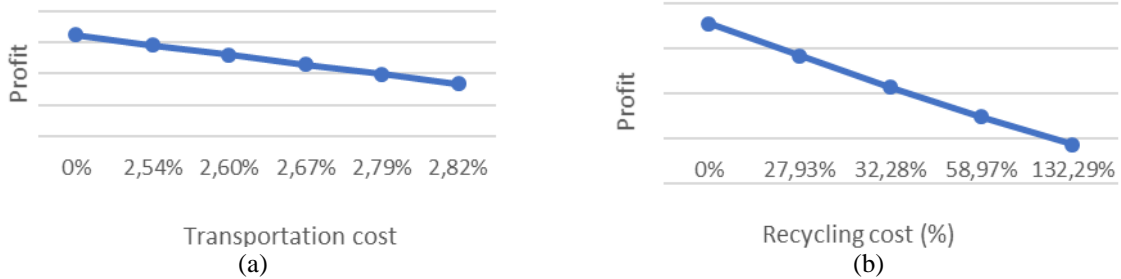


Figure 4 Tradeoffs between: (a) Transportation cost vs. profit; (b) Recycling cost vs. profit

4.3. Service Level (Safety Stock) vs. Profit

An investigation into the link between service level and profit is important to understand the function of service operations and a firm’s profitability (Kamakura et al., 2002). The results of this study indicate that the change in unused battery service level, which can be a linear relationship with safety stock, does not affect the decision variables for the purchase quantity of unused batteries, the sales quantity of lead alloy and plastic, and the inventory of unused batteries, lead alloy and plastic. The lower service level value causes safety stock to decline (see Figure 5). The change in the service level of unused batteries causes total profit to decline by an average of 0.36% with every increase of service level of 5%.

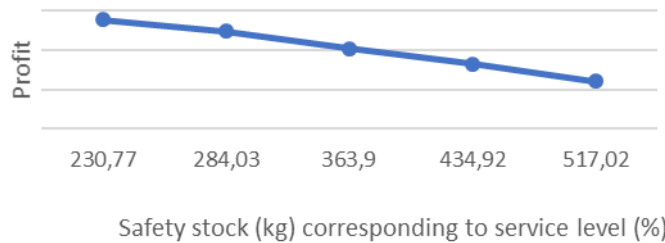


Figure 5 Sensitivity of service level of unused batteries to total profit

The change in lead alloy service level does not affect the decision variables for the purchase quantity of unused batteries, the sales quantity of lead alloy and plastic, or the inventory of unused batteries, lead alloy and plastic. The lower service level causes total profit to decrease (see Figure 6a). Furthermore, the change in the service level of lead alloy causes total profit to decline by an average of 4.75% with every increase of service level of 5%.

There is a change in the decision variables for the purchase quantity of unused batteries, and the sales quantity of lead alloy and plastic, as consequences of the change in service level, whereas the inventory of unused batteries, lead alloy and plastic does not change (see Figure 6b). The change in the service level of plastic causes total profit to decline by an average of 5% with every increase of service level of 5%. These results are relevant to the finding of previous research, which showed that the replenishment quantity of a product affects service level (Minner & Transchel, 2010).

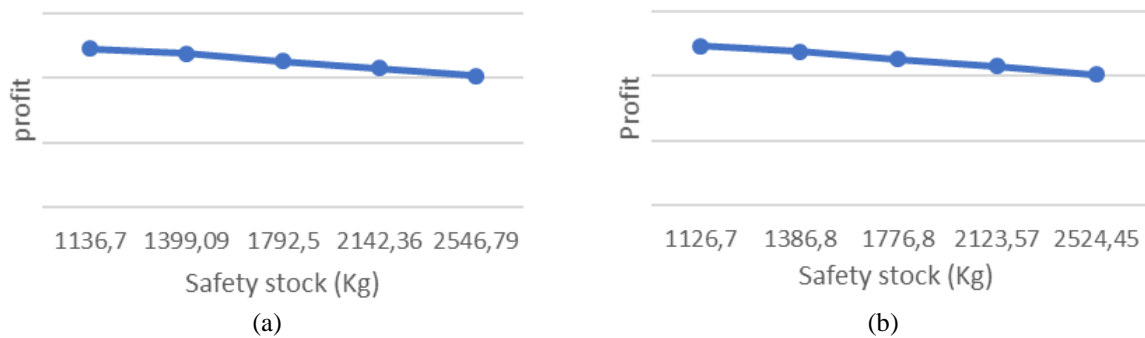


Figure 6 Safety stock of: (a) lead alloy vs. profit; (b) plastic vs. profit

5. CONCLUSION

Most researchers in developing a mathematical model of RL networks have only considered the costs associated with transportation and disassembly costs, while RL network models of recycled batteries have been paid little attention in terms of the inclusion of environmental implications. This study has developed a mathematical model using linear programming for the RL network of battery recycling with multi-period planning. The proposed model takes into account various parameters, including the holding cost of batteries, lead alloy and plastics. The results indicate that the parameters associated with transportation, disassembly and inventory decisions, such as holding costs and service levels, impact significantly on profit.

The results of the sensitivity analysis show that the manufacturing process in the recycling centers is interconnected with the supply and demand from the collection centers and factories respectively. The development of mathematical models of RL in further research needs to consider the forward logistic network for closed loop supply chain purposes. Integration of both flows of the logistic network would improve the performance of the model, as well as the level of implication of associated parameter changes to the broader supply chain.

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