A Regular Production-Remanufacturing Inventory Model for a Two-Echelon System with Price-dependent Return Rate and Environmental Effects Investigation

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Abstract. Product take-back recovery has currently became a promising effort for companies in order to create a sustainable supply chain. In addition, some restrictions including government regulations, social-ethical responsibilities, and up to economic factors have contributed to the reasons for the importance of product take-back recovery. This study aims to develop an inventory model in a system of reverse logistic management consisting of a manufacturer and a collector. Recycle dealer collects used products from the market and ships it to manufacturer. Manufacturer then recovers the used products and sell it eventually to the market. Some recovered products that can not be recovered as good as new one will be sold to the secondary market. In this study, we investigate the effects of environmental factors including GHG emissions and energy usage from transportation, regular production, and remanufacturing operations conducted by manufacturer and solve the model to get the maximum annual joint total profit for both parties. The model also considers price-dependent return rate and determine it as a decision variable as well as number of shipments from collector to manufacturer and optimal cycle period. An iterative procedure is proposed to determine the optimal solutions. We present a numerical example to illustrate the application of the model and perform a sensitivity analysis to study the effects of the changes in environmental related costs on the model’s decision.

Keywords: Inventory model, reverse logistics, collector, regular production, manufacturing remanufacturing, refurbishing, carbon emissions, price-dependent return rate

1. Introduction

Nowadays, environmental and sustainability issue have become a promising market-trend among practitioners and researchers, particularly in the sector of industrial and business [1]. In the last two decades, there had been rapidly growth various insights of production systems, logistics, supply chain, up to product design that carry out the concept of ‘environmental friendly’. One idea that began to be applied by many global industry companies to maintain their sustainability is reverse logistics. According to [2] reverse logistics is defined as a set of activities that associated with the management of used items to be recovered. They underline that the term recovery itself can simply be either direct reselling a product to the market or enclosed by some particular processes including collection, inspection, cleaning, disassembly, and any other related processes that in the end will lead to remanufacturing or recycling. Thierry et al. [4] categorized five types of recovery processes in accordance with its typical characteristics that are, repair, recycle,
remanufacture, refurbish, and cannibalization. A company that considers implementing the system of reverse logistics should differentiate the five processes well to be able to understand which one is the most suitable. Particularly, many companies seek to implement the reverse logistics operations as the related concept actually promises a numerous benefits such as compliance with environmental demands, helps in reducing costs, maintains customer loyalty, shows positive corporate images, improves customer service, increases market share, and provides higher achievement of sustainability goals \[4\], \[5\]. In reality, management of reverse logistics has been broadly implemented by various industry including electronic products and automotive parts, such as steel and glass, printers and photocopiers, tires, ships and aircraft engines, automobiles, air conditioners, televisions, and computer parts \[6\], \[7\].

In reverse logistics some typical industries usually do an alliance between firms that commonly named by joint ventures collaboration. Many operations including building recycling centres, collaborative transportation and logistics, collection of used item, and joint quality control are performed by the help of various firms collaborate in the joint venture \[8\]. According to \[9\], joint venture in reverse supply chain generally accommodates four ways of collaboration including waste disposal, product/part/material in sales, cost sharing, and profit distribution. Vlachos, I \[10\] emphasizes that “joint ventures can be a better mechanism to manage uncertainty in reverse logistics which can be higher than forward supply chains”. Accordingly, many companies have already managed to do the effort as its support to help the system runs more efficiently.

Investigations of reverse logistics management inventory model have attracted the attention of many researchers and practitioners since the year of 1960s. Earlier, the studies about related topics only focused on the single-echelon system and do not accommodate any collaboration among firms in the supply chain \([11\); \[12\]; \[13\]; \[14\]; \[15\]; \[16\]; \[17\]; and \[18\]). At that time, many researchers presumed that the complexity of the system makes it difficult to develop a multi-echelon model \[19\]. Those previous studies also have not yet considered the uncertainties that actually happen in the system of reverse logistics, mainly on the return flow of used item that might be dependable on any other variables such as price, quality, interaction between demand and return rate, and so on \[7\].

Minner, S. \[20\] initiates the case of reverse logistics model in supply chain by extended his work on forward supply chain strategic safety stock placement to reversed one. The objective of the model was to minimize the investment cost related to the safety stock and determined the optimal service times at different locations. Mitra, S. \[19\] developed another model that examined the integration between parties among reverse supply chain. He developed two inventory models with returns consisted of a depot and a distributor under deterministic and stochastic demand and returns. The model considered set-up costs, holding costs, as well as shortage costs for the serviceable inventory stock and determined the optimal values of the policy variables that minimize the cost of the system. Afterwards, he extends the model by incorporating a correlation between demand and returns \[21\].

Chung et al. \[22\] developed a model considering an integration between four parties in reverse supply chain including supplier, manufacturing, retailer, and third party collector. They intended to obtain the optimal decisions of number of shipments between parties and cycle time that minimized the joint inventory costs of the system. The model was then extended by Yuan and Gao \[23\] to the more general multiple cycle production and remanufacturing policies with the same objectives. Other studies that analysed multi-echelon reverse logistics inventory system were also conducted by \[24\], \[25\], \[26\], \[27\], \[28\] and \[29\].

In other study, \[30\] developed a model that investigated a return rate that depends on price and quality factor. They stated that the amount of used item returned to the system were actually relied on purchasing price and quality factor. The higher the purchasing price set by manufacturer, the more amount of used item will be returned to the system because customer might be interested in selling their used products to be exchanged with fresh money. On the contrary, the higher the manufacturer set its acceptable quality level of used item to be collected, the smaller the amount of used item returned to the system. It was due to the quality of the product itself. Many researchers including \[25\], \[27\], \[29\] and \[31\] then further applied the idea of dependent return rate.

Environmental effects consideration is a fresh direction that surely relevant to the current trend of research. Transforming environmental emission and energy usage into cost components in the
system of reverse logistics were done by [32]. In the study, they examined the effects of greenhouse gas (GHG) emission and energy usage on the optimal inventory decisions. They correspondingly found that both costs were proven to have significant influences on the optimal decisions. Therefore, the system should maintain its emission and energy usage hence the cost can be minimized.

In this study, we considers a joint reverse logistics system comprising of two parties, i.e. manufacturer and used item collector, which perform a cooperation in term of inventory. Collector helps the manufacturer to gather the end-of-life products in the market. The model aims to maximize joint total profit per year for both parties and determine the optimal number of shipment, cycle period, and used item purchasing price along with sizing the optimal shipping lot from collector to manufacturer hence the minimum cost and maximum profit can be achieved. We also analyse the environmental effects of green-house-gas emissions and energy usage by considering it as inventory cost components. Hence, the optimal decision will not only minimize the cost related to physical inventory but also environmental cost.

This paper is organized as follows. Section 1 explains about the background of this study and a brief literature review of inventory models that already developed in the related field. Development of the inventory model along with a solution procedure, numerical example and sensitivity analysis are presented in Section 2 and 3, respectively. At the end of the paper, we summarize the results of the study and give directions for future research.

2. Model development

The model developed in this study considers a reversed logistics system comprising of two parties depicted in Figure 1. In which, one party stands for used item collector, hereafter referred as collector, and the other is finished product manufacturer.

![Figure 1. Inventory system of reverse logistics within two parties.](image)

A collector is responsible for collecting end-of-life (EoL) items from the market. Collected used items will be delivered lot-by-lot to the manufacturer in $Q$ unit and $k$ deliveries and be hold respectively at a recoverable stock. The manufacturer inspects all of the recoverable items and sorts them subsequently to be remanufacturable, for items with a higher quality level, and otherwise, refurbishable. Refurbishable items that already experienced refurbishing process will be immediately sold to secondary market at a lower price. In order to fulfil demand at the primary market, manufacturer performs two production activities, i.e. remanufacturing and manufacturing (regular production). Afterwards finished-good items will be hold at serviceable stock. As defined by [3], remanufacturing is a process of reconditioning a used product to as-good-as-new state. Whereas manufacturing is a process to transform a completely raw material into finished-good products. Both processes are done sequentially in one period $T$. 
We consider a return rate which value depends on purchasing/collection price from the market. El Saadany and Jaber [30] stated that return rate, \( U \), is a portion of annual demand, \( D_m \), that is returned to the system and formed as a function of price and quality, with \( 0 < U(p, q)/D < 1 \). In this study, we consider that price factor \( (f_p) \) is more worthy to be examined instead of quality factor, since the focus of this model is nothing but to maximize the financial profit of both parties. According to El Saadany and Jaber (2010), the function of return rate that depends on price factor is formulated below.

\[
f_p = (1 - ae^{\theta p})
\]

with, \( 0 < a < 1 \) and \( \theta > 1 \).

We begin the environmental effects investigation by calculating GHG emissions cost and energy usage cost that generated by some processes, including manufacturing, remanufacturing, as well as transportation related activities. The function of GHG emission cost and energy usage cost related to remanufacturing, manufacturing, and transportation activities were adopted from [32] which originally taken from [33].

The objective function of this model is to maximize the annual joint total profit (AJTP) for both parties and subsequently determine the following decision variables:

- \( k \) : number of delivery from the collector to the manufacturer (delivery/year);
- \( \rho \) : price factor, ratio of the used item purchasing price to raw material purchasing price (where \( 0 \leq \rho \leq 1 \));
- \( T \) : cycle period (year), consisting of one cycle of remanufacturing and one cycle of regular production in one \( T \).

Whereas the parameters used in the model are denoted by these following notations:

- \( D_m \) : annual demand rate (units / year);
- \( U(p) \) : annual return rate of used items (units / year), \( U(p) = D_m(1 - ae^{\theta p}) \);
- \( A_1 \) : set up cost for the collector ($ / batch);
- \( A_2 \) : ordering cost for the manufacturer’s recoverable items ($ / order);
- \( A_m \) : manufacturing set up cost ($ / batch);
- \( A_r \) : remanufacturing set up cost ($ / batch);
- \( H_1 \) : annual holding cost for the collector ($ / unit / year);
- \( H_2 \) : annual holding cost for the recoverable item stock ($ / unit / year);
- \( H_3 \) : annual holding cost for the serviceable item stock ($ / unit / year);
- \( K_1 \) : fixed cost to process the manufacturer’s orders ($);
- \( P_u \) : used item purchasing price ($/unit), \( P_u = \rho P_{rm} \) with \( P_u \leq P_{rm} \);
- \( P_c \) : collector selling price of the used items ($ / unit);
- \( P_{rm} \) : purchasing cost for raw material in the manufacturing activities ($ / unit);
- \( P_{m} \) : selling price of the finished product to the primary market ($);
- \( P_f \) : selling price of the refurbished product to the secondary market ($);
- \( C_{ins} \) : inspection and sorting cost per used item ($ / unit);
- \( c_p \) : manufacturing variable cost ($ / unit);
- \( c_r \) : remanufacturing variable cost ($ / unit);
- \( c_f \) : refurbishing cost ($ / unit);
- \( R \) : annual rate of remanufacturing, \( R > D_m \) (units/year);
- \( P \) : annual rate of manufacturing, \( P > D_m \) (units/year);
- \( f \) : proportion of refurbished item to used item (\( 0 < f < 1 \));
- \( F_t \) : fixed cost per truck per trip ($ / trucks);
- \( t_c \) : truck capacity (unit / truck);
- \( g_t \) : number of gallons per truck per distance travelled (gallons/truck);
- \( e_t \) : amount of GHG emissions from one gallon of diesel-truck fuel (ton/gallon);
- \( C_{ec} \) : carbon emissions cost per ton of GHG emissions ($ / ton);
- \( a_p \) : emissions function parameter for the manufacturing (ton year^2/unit^3);
- \( b_p \) : emissions function parameter for the manufacturing (ton year/unit^2);
- \( c_p \) : emissions function parameter for the manufacturing (year/unit);
\(a_r\) : emissions function parameter for the remanufacturing (ton year\(^2\)/unit\(^3\));
\(b_r\) : emissions function parameter for the remanufacturing (ton/year/unit\(^2\));
\(c_r\) : emissions function parameter for the remanufacturing (ton/unit);
\(C_{en}\) : cost of energy ($/KWh);
\(c_0\rho\) : the required energy at the machine to manufacture one unit (KWh/unit);
\(c_1\rho\) : the required energy per year when manufacturing is idle (KWh/year);
\(c_0r\) : the required energy at the machine to remanufacture one unit (KWh/unit);
\(c_1r\) : the required energy per year when remanufacturing is idle (KWh/year);
\(TC_{ri}\) : annual total inventory cost of the recoverable item ($);
\(TC_{si}\) : annual total inventory cost of the serviceable item ($);
\(TC_M\) : annual total inventory cost for the manufacturer ($);
\(TC_C\) : annual total inventory cost for the collector ($);
\(TP_M\) : annual total profit for the manufacturer ($);
\(TP_C\) : annual total profit for the collector ($);
\(AJTP\) : annual joint total profit of the proposed system ($).

The following assumptions used in the proposed model are listed below:

1. Finite production and remanufacturing rates;
2. Deterministic, constant, and known demand rate;
3. Remanufactured items have the quality as-good-as-new-one;
4. Customer can not distinguish between remanufactured and newly manufactured items;
5. Perfect production processes in the remanufacturing and manufacturing operations;
6. Lead time is zero;
7. Unlimited storage capacity is available;
8. Land transportation is used.

The collector and manufacturer stock levels are shown in Figure 2.

**Figure 2.** The collector stock level and the manufacturer stock level in one period \(T (k=3)\).

A. **Manufacturer Inventory Model**

The manufacturer hold two types of stock, which are serviceable stock and recoverable stock. Costs related to the serviceable stock \((TC_{si})\) consists of holding cost \((HC_{si})\), production setup cost
(SCa), variable production cost (CPa), variable remanufacturing cost (CRa), raw material purchasing cost (Cma), GHG emission cost (CGHa), and cost related to energy usage (Ca), which is expressed in Equation (2).

\[ TCA = HC_{ai} + SC_{ai} + CP_{ai} + CR_{ai} + CGH_G + C_{pm} + C_n \]

\[ = \frac{H_1(1-f)U}{2T} + \frac{D_{ma}^2(1-f)U^2}{2T^2} + A_m + Ar + C_pD_m(1-(1-f)U) + C_a(1-f)U \]

\[ + \frac{C_{ce}(1-f)U + C_{cc}(1-f)^2U}{D_m} + C_{cm}(1-f)U + \left(\frac{C_{pm} + C_{pc}((1-f)U)}{D_m}\right) \]  

(2)

Costs related to the recoverable stock (TCa) consists of holding cost (HCa), ordering cost (OCa), purchasing cost (PCa), inspection cost (ICa), and refurbishing cost (FCa) as formulated in Equation (3) below.

\[ TCA = HC_{ai} + OC_{ai} + PC_{ai} + IC_{ai} + FC_{ai} = \frac{TCA}{T} + C_{co}U + C_{fj}U + P_cU + \left(\frac{(1-f)U}{2R}\right) \]  

(3)

The manufacturer annual profit is obtained from subtracting the manufacturer inventory cost from the manufacturer revenue. Hence, we obtain the following equation.

\[ TP_m = D_mP_m + fUP_f^* - TCA * TCA \]  

(4)

B. Collector Inventory Cost

The collector inventory cost (TCP) consists of holding cost (HCp), collection cost (PCC), transportation cost (TCP), setup cost (SCC), and GHG emission cost of transportation activities (CGHGt) as formulated in Equation (5) below.

\[ TCP = HC_C + PC_C + SC_C + TCP + CGHG_t \]

\[ = \frac{H_1(1-f)U}{2R} + \frac{D_{mp}^2(1-f)U^2}{2R^2} + A_m + Ar + C_pD_m(1-(1-f)U) + C_a(1-f)U \]

\[ + \frac{C_{ce}(1-f)U + C_{cc}(1-f)^2U}{D_m} + C_{cm}(1-f)U + \left(\frac{C_{pm} + C_{pc}((1-f)U)}{D_m}\right) \]  

(5)

The collector annual profit is obtained by subtracting the collector inventory cost from the collector revenue as shown by Equation (6) and subsequently, the annual joint profit for manufacturer-collector inventory system is given by Equation (7).

\[ TP_C = P_cU - TCP \]  

(6)

\[ AJTP = TP_m + TP_C \]  

(7)

3. Solution procedure

In this study, we intend to maximize \( AJTP(T, k, \rho) \) by determining the optimal value of \( T, k, \) and \( \rho. \) The optimal solutions of \( T \) are found by taking the first partial derivative of \( AJTP(T, k, \rho) \) with respect to \( T, \) then setting the result to zero. Hence, we obtain the optimal values of \( T \), denoted by \( T^* \), as follows.

\[ \frac{dAJTP(T, k, \rho)}{dT} = \frac{A_m + A_r}{T^2} + \frac{A_{2k} + A_1 + kK_1}{T^2} \cdot \frac{H_1(U + \rho(U)}{2R} \cdot \frac{H_3(1-f)U + C_{pc}((1-f)U)}{D_m^2} \]

\[ + \frac{H_2(1-f)U + C_{pm}((1-f)U)}{D_m^2} \cdot \frac{H_4(1-f)U + C_{pc}((1-f)U)}{2R} \]  

(8)
Optimization results based on given numerical data.

Table 1. Optimization results based on given numerical data.

| ρ    | U(ρ) | k*  | T*  | T_R | T_F | Q    | TP_m | TP_D | AJTP  |
|------|------|-----|-----|-----|-----|------|------|------|-------|
| 0.45 | 78   | 1   | 603 | 141 | 462 | 78   | $8,518.48$ | $1,667.69$ | $10,249.17$ |
| 0.46 | 80   | 1   | 595 | 143 | 452 | 80   | $8,552.10$ | $1,697.73$ | $10,249.80$ |
| 0.47 *| 83 * | 1 * | 584 * | 145 * | 439 * | 83 * | $8,507.97$ * | $1,749.68$ * | $10,257.65$ * |

The optimal value of k denoted by \( k^* \) could be obtained by letting the derivative of \( AJTP(T, k, \rho) \) with respect to \( k \) equals to zero and then substituting the value of \( T^* \) in equation (9) to \( k \). Thus, we obtain the following function

\[
k^*(\rho) = \frac{\sqrt{\frac{D_m k(A_2+k A_1+2 k H_1+c_0 P R)}{D_m H_2 k^2 - 2(1+f) H_2 k P R^2 - D_m^2 H_2 k (P-2(1+f)U) U + (1+f)(1+f) H_2 P R^2 U + H_2 k (1+f) R U - P R^2 U + (1+f) U)}}{\sqrt{(A_2-K_1)D_m H_2 k^2 - 2(1+f) H_2 k P R^2 - D_m^2 H_2 k (P-2(1+f)U) U + (1+f)(1+f) H_2 P R^2 U + H_2 k (1+f) R U - P R^2 U + (1+f) U)}}
\]  

(10)

The optimal values of \( T, k, \) and \( \rho \) that minimize \( AJTP(T, k, \rho) \) for the value of \( 0 < \rho \) \leq 1 \) is derived by the following solution procedure.

**Step 1** For each value of \( \rho \) for \( 0 < \rho \leq 1 \), calculate the value of \( T \) and \( k \) using equation (9) and (10), respectively. If \( k \) is not an integer, then set \( k = \lfloor k \rfloor \) and \( k = \lfloor k \rfloor \) then continue to step 2.

**Step 2** Calculate the value of \( AJTP(T, k, \rho) \) for \( k = \lfloor k \rfloor \) and \( k = \lfloor k \rfloor \).

**Step 3** Find the combination value of \( T, k, \) and \( \rho \).

After obtaining the optimal value of \( T, k, \) and \( \rho \), then the optimal delivery batch sizes from the collector to the manufacturer could be determined by the following expression

\[
Q^* = \frac{T^* D_m}{k^* (1-f) + \phi}
\]  

(11)

since \( T^* = \frac{(1-f) T}{D_m} \) and \( U = D_m (1-\delta e^{-\delta \phi}) \) hence the value of \( Q^* \) is generated as

\[
Q^* = \frac{T^* D_m}{k^* (1-\delta e^{-\delta \phi})}
\]  

(12)

4. Numerical example and sensitivity analysis

To illustrate the application of the proposed model, let us consider the inventory system with the following data adopted from [32] and [30]: \( D_m = 200 \) units/year, \( P_m = $20 \), \( R = 250 \) units/year, \( P = 220 \) units/year, \( H_2 = $2.5 \) unit/year, \( A_1 = $100 \) batch, \( C_{ic} = $1 \) unit, \( C_f = $5 \) unit, \( H_1 = $3.5 \) unit/year, \( A_2 = $150 \) batch, \( A_3 = $100 \) batch, \( C_p = $10 \) unit, \( C_c = $5 \) unit, \( P_m = $80 \) unit, \( P_f = $25 \) unit, \( f = 0.4 \), \( \delta = 1.5 \), \( \theta = 2 \), \( F_2 = 100 \) units, \( H_1 = $3 \) unit/year, \( A_1 = $50 \) batch, \( K_1 = $50 \), \( g = 375 \) gallons/truck, \( e = 0.1008414 \) tons/gallon, \( C_m = $10 \) ton, \( t_e = 350 \) units/truck, \( c_{ap} = 0.00000003 \), \( b_p = 0.0012 \), \( c_p = 1.4 \), \( a = 0.0000000833 \), \( b_i = 0.002 \), \( c_i = 1.4 \), \( c_i = 25 \), \( c_i = 500,000 \), \( c_i = 10 \), \( c_i = 300,000 \), and \( c_i = 0.05 \) KWh. By using the above solution procedure, we generate the results that maximize \( AJTP(k, T, \rho) \). The optimization results are shown in Table 1.
As shown in Table 1, it is clear that AJTP would be maximized at $10,257.65 for $\rho^*=0.47$ $(P_c=0.47 \times \$20=\$9.4)$, $k^*=1$ delivery, $T^*=584$ days, and $Q^*=83$ units. The results suggest that the system would be equally profitable for both parties as long as decision variables $k$, $T$, and $\rho$ are determined at their optimal levels. The manufacturer should perform remanufacturing phase for 145 days, and change to manufacturing operation immediately after remanufacturing phase was finished, for the period of 439 days.

As the value of $\rho$ increases from its initial value, 0.01, AJTP is keep increasing and finally reaches the maximum level at 0.47 before it is gradually falling down and hit the rock bottom at $\rho=1$. The results prove that $\rho$ gives concave effects on AJTP. Graphical plot of the effects of $\rho$ on AJTP is represented in Figure 3.

![Figure 3. Graphical plot of $\rho$ on AJTP.](image)

Here, we also conduct a simple sensitivity analysis to study the environmental effects on AJTP. The analysis is done by changing the value of $C_{ec}$, denotes the cost related to GHG emission in term of $/ton$, and $C_en$, denotes the cost related to energy usage in term of $/KWh$. The results are shown in Table 2 and 3 below.

**Table 2. Effects of $C_{ec}$ on model’s decision.**

| $C_{ec}$ | $\rho$ | $U(\rho)$ | $k^*$ | $T^*$ | $T_R$ | $T_P$ | $Q$ | $TP_m$ | $TP_C$ | AJTP  |
|---------|-------|-----------|------|------|------|------|----|-------|-------|------|
| $\$10$  | 0.47  | 83        | 1    | 584  | 145  | 439  | 83 | $8,507.97$ | $1,749.68$ | $10,257.65$ |
| $\$20$  | 0.47  | 83        | 1    | 584  | 145  | 439  | 83 | $8,496.96$ | $1,660.01$ | $10,156.97$ |
| $\$30$  | 0.44  | 76        | 1    | 610  | 139  | 471  | 76 | $8,588.72$ | $1,472.69$ | $10,061.40$ |
| $\$40$  | 0.44  | 76        | 1    | 610  | 139  | 471  | 76 | $8,577.66$ | $1,390.57$ | $9,968.24$  |
| $\$50$  | 0.41  | 68        | 1    | 644  | 131  | 513  | 68 | $8,683.38$ | $1,198.95$ | $9,882.33$  |

The results in Table 2 and 3 indicate that $C_{ec}$ and $C_en$ affect almost all of the model’s decisions, including $\rho^*$, $T^*$, and $Q^*$, except for $k^*$. The higher the cost related to the environment that should be paid by both parties, the lower the profit that could be achieved by the system. The parameter $C_{ec}$ and $C_en$ directly affect the cost related to GHG emission and cost related to energy usage. Unpredictably, the changes in those parameters actually give significant impact on $\rho^*$ and $T^*$ (the changes in $Q$ are not considered since the value of $Q$ is dependent on $U(\rho)$). Increased value of $C_{ec}$ causes the optimal cycle period, $T^*$ to be longer.

**Table 3. Effects of $C_{en}$ on model’s decision.**

| $C_{en}$ | $\rho$ | $U(\rho)$ | $k^*$ | $T^*$ | $T_R$ | $T_P$ | $Q$ | $TP_m$ | $TP_C$ | AJTP  |
|---------|-------|-----------|------|------|------|------|----|-------|-------|------|
| $\$0.05$ | 0.47  | 83        | 1    | 584  | 145  | 439  | 83 | $8,507.97$ | $1,749.68$ | $10,257.65$ |
| $\$0.15$ | 0.47  | 83        | 1    | 584  | 145  | 439  | 83 | $8,305.28$ | $1,749.68$ | $10,054.97$ |
therefore, we guaranteed global optimum decisions. Maximum annual profit for the system. The optimization of the model is done analytically. Cycle period, number of shipments, and used item purchasing price are optimized to achieve optimal return rate is assumed to be a demand-like function of used item purchasing price. The optimal is the dependent return rate that rely on the purchasing price of used items. In the proposed model, optimal solution for the parties involved in the operation of joint ventures. Another consideration process in the form of emission costs and energy usage costs. In addition, it also provides an this model has considered the environmental impact of production and the remanufacturing dependent return rate and environmental effects investigations. Compared with previous studies, the inventory model developed in this study has considered a variable return rate that is affected by the purchasing price of used items. Accordingly, we may say that the model is suitable to be applied in manufacturing cases which the offered purchasing price influences the behaviour of customer to resell their used item. It is relevant to the real system since customer is more willingly to sell the used product to manufacturer when the bargaining position is higher. It enables the system to control the amount of returned item by determining the correct used item purchasing price.

5. Conclusion

This study proposes a collector-manufacturer reverse logistic inventory model with price-dependent return rate and environmental effects investigations. Compared with previous studies, this model has considered the environmental impact of production and the remanufacturing process in the form of emission costs and energy usage costs. In addition, it also provides an optimal solution for the parties involved in the operation of joint ventures. Another consideration is the dependent return rate that rely on the purchasing price of used items. In the proposed model, return rate is assumed to be a demand-like function of used item purchasing price. The optimal cycle period, number of shipments, and used item purchasing price are optimized to achieve maximum annual profit for the system. The optimization of the model is done analytically therefore we guaranteed global optimum decisions.

From the provided numerical example, the results point out that to achieve maximum profit of the system, manufacturer should perform shorter period of remanufacturing and longer period of manufacturing. Price factor is numerically proven to give convex effects on AJTC, therefore an optimum value of \( \rho \) should be generated. The optimal number of shipments is one shipments per year with delivery lot sizes equal to its return rate per year. This means that it is more beneficial for the system to hold more stock rather than to order/deliver used item too frequent. The results of environmental effects investigation show that costs parameters related to GHG emissions per ton and energy usage per KWh give significant impact on \( \rho \) and \( T \) respectively. Hence to maintain its profits, the system should reduce its costs related to GHG emissions and energy usage.

The extension of the proposed study is to consider real stochastic demand and return rate. Accordingly, decisions related to stochastic condition including safety stock and reorder point should be determined. A second extension is to consider more parties in the supply chain, such as supplier and retailer, hence the model will become more comprehensive to be applied in real supply chain. Another direction is to include imperfect manufacturing and remanufacturing processes where defective items are either be reworked, resold, or scrapped.

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| $0.25  | 0.5  | 90  | 1   | 560 | 151 | 409 | 90  | $8,003.89 | $1,854.71 | $9,858.60 |
|-------|------|-----|-----|-----|-----|-----|-----|----------|----------|----------|
| $0.35 | 0.5  | 90  | 1   | 560 | 151 | 409 | 90  | $7,803.49 | $1,854.71 | $9,658.20 |
| $0.45 | 0.5  | 90  | 1   | 560 | 151 | 409 | 90  | $7,603.08 | $1,854.71 | $9,457.79 |

Whereas, increasing \( C_{ra} \) lead to a lower optimal purchasing price of used item (\( \rho \)). On the contrary, increased value of \( C_{re} \) cause \( T \) to be shorter and lead to a higher \( \rho \). From those results, we can conclude that \( C_{ra} \) and \( C_{re} \) give different effects on model’s decision. In a situation where the uncontrollable costs are increasing, i.e. \( C_{ra} \) and \( C_{re} \), the system would maintain the maximum level of profit by controlling the optimal value of decision variables, such as \( \rho \) and \( T \) for this case.
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