Design of Closed-Loop Supply Chain Model with Efficient Operation Strategy

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Abstract. In this paper, a closed-loop supply chain model with efficient operation strategy (CLSC-OS) is proposed. In the CLSC-OS, various facilities which can be used in forward logistics (FL) and reverse logistics (RL) are taken into consideration. A mathematical formulation is proposed to design the CLSC-OS and it is implemented using genetic algorithm (GA) approach. In numerical experiment, for efficient operation strategy, several scenarios using various factors such as remanufacturing rate, profit premium rate, discount rate, and return rate based on revenue-cost rate is considered and analyzed. Experimental results shows that discount rate and profit premium rate have a significant influence on revenue-cost rate.

Keywords: Closed-loop supply chain · Efficient operation strategy · Forward logistics · Reverse logistics · Genetic algorithm

1 Introduction

In general, designing closed loop supply chain (CLSC) model is to maximize the utilization of resources. Especially, return management such as reuse and resale of the recovered parts and products has been focused on many companies. For example, by 1997, approximately 73,000 U.S. companies had earned $53 billion though resale activities of remanufactured products [1]. This means that return management using used product becomes more and more important.

Return management using used product is usually consisted of three aspects. The first aspect is the operational management of returned product, the second one is that of remanufacturing activity, and the third one is that of secondary market [6]. Ozkir and Basligil considered the operational management of returned product [8]. They found that regulating the rate of returned product can increase the total profit and revenue. Subramoniam found that remanufacturing activities can increase profit, save resource and energy, create new market [9]. Van Daniel et al. suggested that con-sidering both new market with new product activity and secondary market with resale activity can get more profit than the new market alone [7].

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However, unfortunately, little attention to the relationship among the three aspects of return management has been done in conventional studies. Therefore, in this paper, we consider the relationship based on various scenarios using remanufacturing rate, profit premium rate, discount rate, and return rate and analyze which factor can be an important one to increase total profit.

For achieving this objective, a CLSC model with efficient operation strategy (CLSC-OS) is proposed in Sect. 2. The CLSC-OS is consisted of various facilities such as supplier, product manufacturer, retailer, recovery center, and secondary market at each stage. In Sect. 3, a mathematical formulation is proposed for implementing the CLSC-OS. The mathematical formulation is represented as a nonlinear mixed integer programming (NIMIP). The NIMIP is implemented using a genetic algorithm (GA) approach in Sect. 4. In numerical experiment of Sect. 5, the CLSC-OS is presented and various scenarios using the CLSC-OS is considered. For various scenarios, remanufacturing rate, profit premium rate, discount rate, and return rate are considered and they all are used for analyzing the revenue-cost rate resulting from the implementation of the CLSC-OS. Some conclusions and a room for improvement to future study are followed in Sect. 6.

2 Proposed CLSC-OS

The proposed CLSC-OS is an integrated model combining forward logistics (FL) and reverse logistics (RL), which is consisted of suppliers in areas 1, 2, 3, and 4, product manufacturer, part inventory distribution center, product distribution center and retailer in FL and customer, collection center, recovery center, secondary market and waste disposal center in RL. For effective use of the recovered parts from recovery center, part inventory distribution center is also taken into consideration. The conceptual network structure of the proposed CLSC-OS is shown in Fig. 1.

In Fig. 1, the production and recovery flows are as follows. New part types 1, 2, 3, and 4 (NP1, NP2, NP3, and NP4) are produced at the suppliers of areas 1, 2, 3, and 4, respectively. NP1, NP2, NP3, and NP4 are then sent to part inventory distribution center. Recovered parts (RP1, RP2, RP3, and RP4) from recovery center are also sent to part inventory distribution center. Product manufacturer produces product using NP1, NP2, NP3, NP4, RP1, RP2, RP3, and RP4 from part inventory distribution center. The product is sent to retailer through product distribution center and sold to customer. The returned product from customer is collected at collection center and then sent to recovery center. At recovery center, the returned product is checked and classified into recoverable and unrecoverable products. The quality of the recoverable product with a_1% is recovered at recovery center and then resold at secondary market. The unrecoverable product is disassembled into recoverable and unrecoverable parts. The quality of the recoverable part with a_2% is recovered at recovery center and then sent to part inventory distribution center. The unrecoverable part with a_3% is sent to waste disposal center to be burned or landfilled.

Especially, in the proposed CLSC-OS, the part inventory distribution center can regulate the transportation amount of NP1, NP2, NP3, NP4, RP1, RP2,

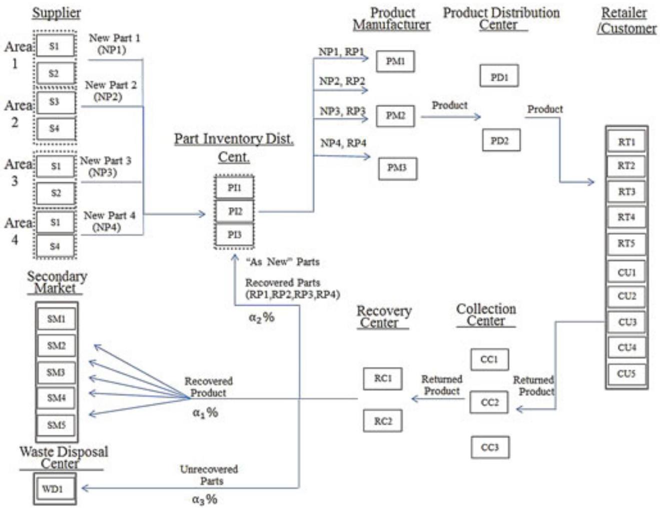

Fig. 1. The conceptual network structure of the CLSC-OS

RP3, and RP4. For instance, if product manufacturer want to produce 100 products and a_2 is 10% (10 recovered parts = 100 returned product ×10%), then part inventory distribution center sends 90 NP1, 90 NP2, 90 NP3, and 90 NP4 as new parts and 10 RP1, 10 RP2, 10 RP3, and RP4 as recovered parts to product manufacturer.

3 Mathematical Formulation

Beofre suggesting the mathematical formulation for the CLSC-OS, the following assumptions should be considered.

- Single product is produced within a fixed period.
- New market (retailer) and resale market (secondary market) are separated.
- The qualities of the new parts (NP1, NP2, NP3, and NP4) from supplier and those of the recovered parts (RP1, RP2, RP3, and RP4) from recovery center are identical.
- All products (new and recovered products) at retailer and secondary market are sold to customer.
- The number of facilities at each stage is known.
- All facilities at retail/customer, secondary market, and waste disposal center should be opened. However, only one facility at supplier, product manufacturer, product distribution center, part inventory distribution center, collection center, and recovery center should be opened, which means that the other facilities at each stage should be closed.
- Fixed costs of all facilities are different and known.
- Unit handling costs of all facilities at same stage are identical and known.

- Unit transportation costs of all facilities at each stageare different and known.
- The handling capacity of the facilities at a stage is the same or greater than that of previous ones.
- The return rate from customer is fixed.
- The discount rates of recovered product and part are calculated according to the quality of returned product and part.

The index sets, parameters, and decision variables for the mathematical formulation are as follows.
Index set

a : index of area at supplier; $a \in A$;
b : index of new product; $b \in B$;
h : index of supplier; $h \in H$;
i : index of part inventory distribution center; $i \in I$;
j : index of product manufacturer; $j \in J$;
k : index of product distribution center; $k \in K$;
l : index of retailer/customer; $l \in L$;
m : index of collection center; $m \in M$;
n : index of recovery center; $n \in N$;
o : index of secondary market; $o \in O$;
p : index of waste disposal center; $p \in P$

Parameter

FDS_{ha} : fixed cost at supplier h of area a;
FDI_i : fixed cost at part inventory distribution center i;
FDO_j : fixed cost at product manufacturer j;
FDD_k : fixed cost at distribution center k;
FDC_m : fixed cost at collection center m;
FDR_n : fixed cost at recovery center n;
UHS_{ha} : unit handling cost at supplier h of area a;
UHO_j : unit handling cost at product manufacturer j;
UHD_k : unit handling cost at product distribution center k;
UHC_m : unit handling cost at collection center m;
UHR_n : unit handling cost at recovery center n;
UHE_e : unit handling cost at secondary market e;
UHW_p : unit handling cost at waste disposal center p;
UTS_{hai} : unit transportation cost from supplier h of area a to part inventory distribution center i;
UTI_{ij} : unit transportation cost from part inventory center i to product manufacturer j;
UTO_{jk} : unit transportation cost from product manufacturer j to product distribution center k;
UTD_{kl} : unit transportation cost from product distribution center k to retailer/customer l;

UTA_{lm} : unit transportation cost from retailer/customer l to collection center m;
UTC_{mn} : unit transportation cost from collection center m to recovery center n;
UTE_{no} : unit transportation cost from recovery center n to secondary market o;
UTI_{ni} : unit transportation cost from recovery center n to part inventory distribution center i;
UTL_{np} : unit transportation cost from recovery center n to waste disposal center p;
KCI_{i} : holding cost at part inventory distribution center i;
UPN_{b} : unit price of new product b;
PRN_{b} : profit premium rate for new product b at retailer l

Decision variables
TCs_{ha} : treatment capacity at supplier h of area a
TCi_{i} : treatment capacity at part inventory distribution center i
TCo_{j} : treatment capacity at product manufacturer j
TCd_{k} : treatment capacity at product distribution center k
TCu_{l} : treatment capacity at retailer/customer l
TCc_{m} : treatment capacity at collection center m
TCe_{n} : treatment capacity for recovered product at recovery center n
TCi_{n} : treatment capacity for recovered part at recovery center n
TCl_{n} : treatment capacity for unrecovered part at recovery center n
TCe_{e} : treatment capacity at secondary market e
TCw_{p} : treatment capacity at waste disposal center p
Q : quantity of new product
Rt : return rate
DS_o : discount rate for recovered product
DS_i : discount rate for recovered part
ys_{ha} : takes the value of 1 if suppler h at area a is opened and 0 otherwise
yi_i : takes the value of 1 if part inventory distribution center i is opened and 0 otherwise
yo_j : takes the value of 1 if product manufacturer j is opened and 0 otherwise
yd_k : takes the value of 1 if product distribution center k is opened and 0 otherwise
yc_m : takes the value of 1 if collection center m is opened and 0 otherwise
yr_n : takes the value of 1 if recovery center n is opened and 0 otherwise

Using the above mentioned index sets, parameters, and decision variables, the mathematical formulation is suggested as follows:

Maximize Total Revenue (TR)

$$\begin{aligned}\mathrm{TR} =&\text{revenue of new product} + \text{ revenue of recovered product}\\ &+ \text{revenue of recovered part}\end{aligned} \tag{1}$$

$$= \sum_{i} Q \times \mathrm{PRN}_b + \sum_{o} Q \times \mathrm{UPN}_b \times \alpha_1 \times DS_o + \sum_{o} Q \times \mathrm{UPN}_b \times \alpha_2 \times DS_i, \quad (2)$$

where

$$\mathrm{UPN}_b = (\mathrm{TCF} \times (1 + \mathrm{PRN}_b))\,/Q. \quad (3)$$

Minimize Total Cost (TC)

$$\mathrm{TC} = \text{total cost of FL (TCF)} + \text{total cost of RL (TCR)}. \quad (4)$$

$$\begin{aligned}
\mathrm{TCF} &= \text{total FL fixed cost} + \text{ total FL handling cost} \\
&\quad + \text{total FL transportation cost} \\
&= \sum_{a}\sum_{h} (\mathrm{FDS}_{ha} \times ys_{ha}) + \sum_{i} (\mathrm{FDI}_i \times yi_i) + \sum_{i} (\mathrm{FDO}_j \times yo_j) \\
&\quad + \sum_{a}\sum_{h} (\mathrm{UHS}_{ha} \times TCs_{ha} \times ys_{ha}) + \sum_{j} (\mathrm{UHO}_j \times TCo_j \times yo_j) \\
&\quad + \sum_{j} (\mathrm{UHD}_k \times TCd_k \times yd_k) + \sum_{a}\sum_{h}\sum_{i} (UTS_{hai} \times TCs_{ha} \times ys_{ha} \times yi_i) \\
&\quad + \sum_{ij} (\mathrm{UTI}_{ij} \times TCi_i \times yi_i \times yo_j) + \sum_{jk} (\mathrm{UTO}_{jk} \times TCo_j \times yo_j \times yd_k) \\
&\quad + \sum_{kl} (\mathrm{UTD}_{kl} \times TCd_k \times yd_k)\,,
\end{aligned} \quad (5)$$

$$\begin{aligned}
\mathrm{TCR} &= \text{total RL fixed cost} + \text{total RL handling cost} \\
&\quad + \text{total RL transportation cost} + \text{holding cost} \\
&= \sum_{m} (\mathrm{FDC}_m \times yc_m) + \sum_{i} (\mathrm{FDR}_n \times yr_n) + \sum_{a}\sum_{h} (\mathrm{UHC}_m \times TCc_m \times yc_m) \\
&\quad + \sum_{n} (\mathrm{UHR}_n \times TCe_n \times yr_n) + \sum_{n} (UHR_n \times TCi_n \times yr_n) \\
&\quad + \sum_{n} (\mathrm{UHR}_n \times TCl_n \times yr_n) + \sum_{e} (\mathrm{UHE}_e \times TCe_e) + \sum_{p} (\mathrm{UHW}_p \times TCw_p) \\
&\quad + \sum_{lm} (\mathrm{UTA}_{lm} \times TCu_l \times yc_m) + \sum_{mn} (\mathrm{UTC}_{mn} \times TCc_m \times yc_m \times yr_n) \\
&\quad + \sum_{no} (\mathrm{UTE}_{no} \times TCe_n \times yr_n) + \sum_{ni} (\mathrm{UTI}_{ni} \times TCi_n \times yr_n) \\
&\quad + \sum_{ni} (\mathrm{UTL}_{np} \times TCl_n \times yr_n) + \sum_{i} (\mathrm{KCI}_i \times yi_i)
\end{aligned} \quad (6)$$

$$\text{s.t.} \sum_{h} ys_{ha} = 1, \forall a \in A \tag{7}$$

$$\sum_{i} yi_{i} = 1 \tag{8}$$

$$\sum_{j} yo_{j} = 1 \tag{9}$$

$$\sum_{k} yd_{k} = 1 \tag{10}$$

$$\sum_{m} yc_{m} = 1 \tag{11}$$

$$\sum_{n} yr_{n} = 1 \tag{12}$$

$$\sum_{h} (UHS_{hai} \times ys_{ha}) - \sum_{i} (TCi_{i} \times yi_{i}) = 0, \forall a \in A \tag{13}$$

$$\sum_{i} (TCi_{i} \times yi_{i}) - \sum_{j} (UHO_{j} \times yo_{j}) = 0 \tag{14}$$

$$\sum_{i} (\mathrm{UHO}_{j} \times yo_{j}) - \sum_{k} (\mathrm{UHD}_{k} \times yd_{k}) = 0 \tag{15}$$

$$\sum_{k} (\mathrm{UHD}_{k} \times yd_{k}) - \sum_{l} TCu_{l} = 0 \tag{16}$$

$$\sum_{l} TCu_{l} - \sum_{m} (\mathrm{UHC}_{m} \times yc_{m}) = 0 \tag{17}$$

$$\sum_{i} (TCi_{i} \times yi_{i}) - \alpha_{2} \sum_{n} (\mathrm{UHR}_{n} \times yr_{n}) \geq 0 \tag{18}$$

$$\sum_{n} (HCrc_{n} \times x\_rc_{n}) - \alpha_{3} \sum_{p} (UHW_{p} \times yw_{p}) \geq 0 \tag{19}$$

$$\sum_{n} (\mathrm{UHR}_{n} \times yr_{n}) - \sum_{o} (\mathrm{UHC}_{m} \times yc_{m}) = 0 \tag{20}$$

$$\sum_{n} (\mathrm{UHR}_{n} \times yr_{n}) - \alpha_{1} \sum_{e} \mathrm{UHE}_{e} \geq 0 \tag{21}$$

$$ys_{ha} = \{0, 1\}, \forall h \in H, a \in A \tag{22}$$

$$yi_{i} = \{0, 1\}, \forall i \in I \tag{23}$$

$$yo_{j} = \{0, 1\}, \forall j \in J \tag{24}$$

$$yd_{k} = \{0, 1\}, \forall k \in K \tag{25}$$

$$yc_{m} = \{0, 1\}, \forall m \in M \tag{26}$$

$$yr_{n} = \{0, 1\}, \forall n \in N \tag{27}$$

$$\begin{aligned} &\mathrm{UHS}_{hai}, \mathrm{UHO}_{j}, \mathrm{UHD}_{k}, \mathrm{UHC}_{m}, \mathrm{UHR}_{n}, \mathrm{UHE}_{e}, \mathrm{UHW}_{p} \geq 0 \\ &\forall h \in H, a \in A, \forall i \in I, j \in J, \forall k \in K, \\ &\forall m \in M, \forall n \in N, \forall e \in E, \forall p \in P \end{aligned} \tag{28}$$

The objective function is divided into two parts. First part is to maximize total revenue and second one is to minimize total cost. Maximizing the total revenue is represented in Eq. (2) and minimizing the total cost is in Eq. (4). Each objective function should be maximized and minimized under satisfying all constraints which represented from Eqs. (7)–(28). Equations (7)–(12) mean that only one facility at each stage should be opened. Equations (13)–(21) show that the capacity of each opened facility is the same or greater than that of the previous one. Equations (22)–(27) means that each decision variables can take the value 0 or 1. Equation (27) refers to non-negativity.

4 Genetic Algorithm (GA) Approach

Genetic Algorithm (GA) approach was proposed by Goldberg [5] and has been used to solve many optimization problems [3,4,10]. GA approach starts with producing a random initial population and each individual in the population represents a potential solution. The next step is that each individual is selected by evaluating the measure of fitness and producing a next new population. All individuals in the new population are undergoing crossover and mutation operators. For crossover and mutation opera-tors, various methodologies such as one-point crossover operator (1X), two-point crossover operator (2X), and random mutation operator have been developed. After applying the crossover and mutation operators to each individual, an offspring is produced and the fitness is evaluated. These procedure is repeated until a pre-defined stop condition is satisfied or optimal solution already known is located. Finally, the optimal solution is produced.

The GA approach [2,3] for implementing the mathematical formulation in Sect. 3 is as Fig. 2:

```
procedure: GA approach
input: problem data, GA parameters
output: best solution
begin
    t = 0;
    generate initial population randomly P(t) satisfying constraints;
    evaluate P(t) using fitness test by decoding routine;
    while (not termination condition) do
        create N(t) from P(t) by two cut-point crossover routine;
        create N(t) from P(t) by random mutation routine;
        reproduce P(t + 1) from P(t) and N(t) by elitist selection rou-
tine;
        t = t + 1
     end
     output best solution
end;
```

Fig. 2. The GA approach

5 Numerical Experiments

In numerical experiment, various scenarios are considered for evaluating the rate of the total revenue in Eq. (1) and the total cost in Eq. (4). First, a scale for the proposed CLSC-OS is presented in Table 1. As shown in Table 1, numbers of the suppliers (S) at each area, part inventory distribution center (PI), product manufacturer (PM), product distribution center (PD), retailer/customer (RT), collection center (CC), recovery center (RC), secondary market (SM), waste disposal center (WD) are displayed.

Table 1. Scale of the CLSC-OS

No. of S Area 1, 2, 3, 4	No. of PI	No. of PM	No. of PD	No. of RT	No. of CC	No. of RC	No. of SM	No. of WD
4	2	4	2	10	4	2	10	2

Table 2 shows various cases of remanufacturing for returned product at recovery center. a_1, a_2, and a_3 refer to the rates of recovered product, recovered part, and unre-covered part, respectively. For instance, Case 1 means that (i) 60% of all returned products are recovered and sent to secondary market, (ii) 30% of them are recovered and sent to part inventory distribution center and (iii) 10% of them are unrecovered and sent to waste disposal center.

Table 2. Various cases of remanufacturing

Case	a_1	a_2	a_3
1	0.6	0.3	0.1
2	0.6	0.2	0.2
3	0.6	0.1	0.3
4	0.7	0.2	0.1
5	0.7	0.1	0.2
6	0.8	0.1	0.1

Table 3 shows various scenarios. Each scenario has four factors using the case of remanufacturing, return rate, discount rate and profit premium rate. By the each scenario, various relationships between total revenue and total cost are compared. For instance, Scenario 1 indicates that various cases in Table 2 and various profit premium rates (P_m = 0.4, 0.3, 0.2, 0.1, and 0.0) under the fixed values at return rate and discount rate are considered to solve the two mathematical formulations in Eqs. (1) and (4). The computation results are used for comparing the relationships between total revenue and total cost.

Each scenario in Tables 2 and 3 under the scale of the proposed CLSC-OS is implemented using GA approach. The parameters used in GA approach is that population size is 20, crossover rate 0.5, and mutation rate 0.3. The GA approach is executed under the following computation environment: Matlab R2015 under

Table 3. Various scenarios

Scenario	Case	Return rate	Discount rate	Profit premium rate
1	1, 2, 3, 4, 5, 6	1.0	0.5	0.4, 0.3, 0.2, 0.1, 0.0
2	1	1.0	0.5	0.4, 0.3, 0.2, 0.1, 0.0
3	1	1.0	0.5, 0.4, 0.3, 0.2	0.4, 0.3, 0.2, 0.1, 0.0
4	1, 2, 3, 4, 5, 6	0.9	0.5	0.4, 0.3, 0.2, 0.1, 0.0

IBM compatible PC 3.40GHZ processor (Inter Core i7-3770 CPU), 8GB and Window 7.

Figure 3 shows the computation results of total revenue-cost rates in Scenario 1. Each curve with different colors shows the changes of the total revenue-cost rates under the changes of profit premium rate. For instance, the top blue-colored curve shows a fixed values of 1.4 in the total revenue-cost rates of all cases under the fixed values of 0.4 profit premium rate, 100% return rate and 0.5 discount rate. Similar situations are also shown in the other colored-curves. Therefore, the results shown in Fig. 3 indicates that the changes of remanufacturing rate has no significant influence on the increase of total profit.

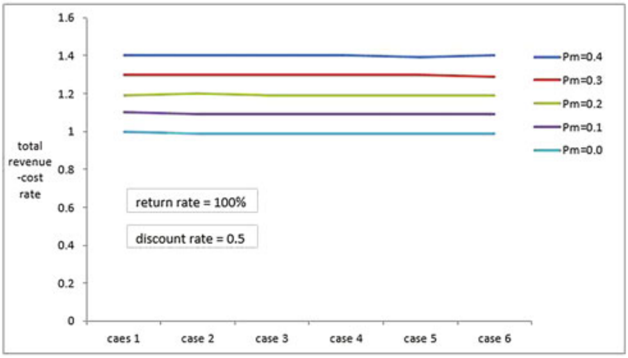

Fig. 3. Computation results of total revenue-cost rates in Scenario 1

Figure 4 shows the changes of the total revenue-cost rates under various profit premium rates, when return and discount rates are fixed at 100% and 0.5, respectively. As the changes from profit premium rate 0.4 to 0.0, the total revenue-cost rate is continuously decreasing. Therefore, the results shown in Fig. 4 indicate that the profit premium rate has significant influence on the increase of total profit.

Figure 5 shows the changes of the total revenue-cost rates for each profit premium rate under various discount rates, when return rate is fixed at 100%. For instance, the top blue-colored curve shows that total revenue-cost rates is

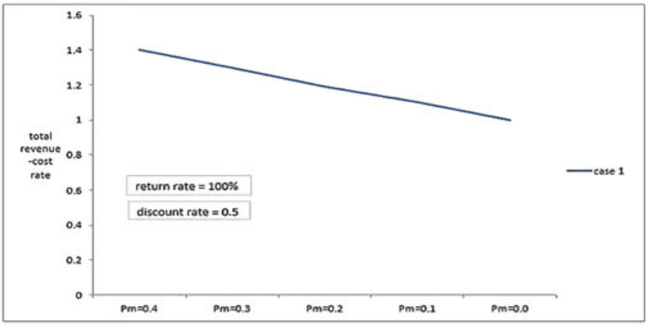

Fig. 4. Computation results of total revenue-cost rates in Scenario 2

increasing according to the changes of discount rate from 0.5 to 0.2. Similar situations are also shown in the other colored-curves. Therefore, the results shown in Fig. 5 indicate that the change of discount rates has significantly influence on the increase of total profit.

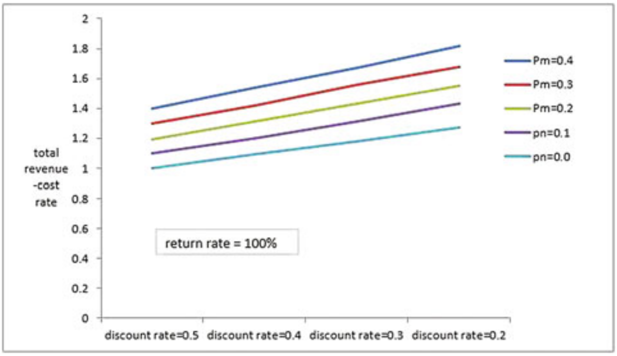

Fig. 5. Computation results of total revenue-cost rates in Scenario 3

Similar to Figs. 3 and 6 shows the computation results of total revenue-cost rates in Scenario 4. Each curve with different colors shows the changes of the total revenue-cost rates under the changes of profit premium rate. For instance, the top blue-colored curve shows a little change around 1.55 for each case when the discount rate and profit premium rate are fixed at 90% and 0.4, respectively. Similar curves are also shown in the profit premium rates 0.3 and 0.0. However, the curves of profit premium rates 0.2 and 0.1 do not show any changes for each case. Therefore, the results shown in Figs. 3 and 6 indicate that the changes of remanufacturing rate and return rates has no significant influence on the increase of total profit, though there is a little changes according to each case.

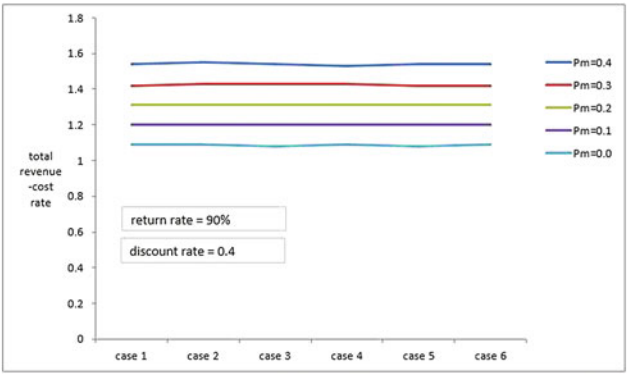

Fig. 6. Computation results of total revenue-cost rates in Scenario 4

6 Conclusion

The first objective of this study is to design a CLSC-OS with various facilities at each stage and the second one is to find a good alternative for increasing total profit under the changes of remanufacturing rate, discount rate, profit premium rate, and return rate.

For achieving the two objectives, the CLSC-OS has been proposed. The proposed CLSC-OS has supplies at areas 1, 2, 3, and 4, product manufacturer, product distribution center, and retailer in FL and customer, collection center, recovery center, secondary market and waste disposal center in RL. This is represented in a mathematical formulation which has two objectives of the maximization of total revenue and the minimization of total cost under various constraints. The mathematical formulation is implemented using GA approach. In numerical experiment, four types of scenarios with the changes of remanufacturing rate, discount rate, profit premium rate, and return rate have been considered and executed using GA approach. The experimental results have shown that the changes of the profit premium rates and the discount rates have no significant influence on the increase of total profit, but the changes of the profit premium rates and the discount rates have significant influence on the increase of total profit. Therefore, decreasing the profit premium rates and the discount rates can be a good alternative for increasing the total profit (= total revenue − total cost) in the proposed CLSC-OS.

However, in this paper, since only four scenarios have been considered, more various scenarios with larger-scaled CLSC-OS will be considered to compare the changes of remanufacturing rate, discount rate, profit premium rate, and return rate. This will be left to future study.

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