A study on closed-loop supply chain model for parts reuse with economic efficiency

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Abstract
This study proposes a basic model for closed-loop supply chains which includes not only traditional forward supply chains for the generation of products but also reverse supply chains for the reuse and recycling of products in consideration of economic efficiency for make-to-order and remanufacturing-to-order companies. The basic model consists of four model components, i.e., clients, manufacturers, suppliers, and remanufacturers. A remanufacturer is added to the previous model of forward supply chains in this study as a new model component which collects used products from clients and provides reusable parts to manufacturers in consideration of the demand of products. Remanufacturers as well as manufacturers and suppliers modify their schedules and negotiate with each other in order to determine suitable prices and delivery times of products. Remanufacturers stimulate clients to discard used products to meet the demand of reusable parts. They can increase the amount of reused products and reduce wastes by creating a balance between supply and demand of reusable parts. A prototype of a simulation system for closed-loop supply chains is developed in order to evaluate the effectiveness of the proposed model and negotiation protocol. Experimental results of the proposed model are compared with the ones of a conventional model which discards the used products without negotiation processes between remanufacturers and clients. Experimental results show that the proposed model can reuse more products than the conventional model.

Key words: Closed-loop supply chain, Reverse supply chain, Scheduling, Genetic algorithm, Negotiation, Make-to-order, Remanufacturing-to-order

1. Introduction

Supply chain management has been investigated for the configuring and controlling of material and information flows among different organizations, such as raw material suppliers, parts suppliers, sub-assembly manufacturers, and assembly manufacturers, as well as among their customers. The trend has been toward even more flexible or dynamic supply chains to find suitable business partners and enter into profitable contracts. Previous studies have proposed a two-layered dynamic supply chain model consisting of clients and suppliers for make-to-order (MTO) companies (Tanimizu, et al., 2006; Tanimizu, et al., 2007). The model provided the negotiation protocol to determine the suitable prices and delivery times of products through the iteration of the negotiation processes between the clients and the suppliers, and the modification processes of the production schedules in the suppliers. The previous model has been extended to a three-layered dynamic supply chain model consisting of the suppliers, the manufacturers, and the clients as a minimum model for the multi-layered dynamic supply chains (Tanimizu, et al., 2013). The extended model also proposed a cooperative negotiation process among the three-layered organizations.

Many companies focus on incorporating environmental concerns into their strategic decisions in the latest survey (BearingPoint, 2008). Green supply chain management (GSCM) has gained increasing attention within both academia and industry (Sarkis, et al., 2011). The green supply chain is an approach which seeks to minimize a product or service’s ecological footprint. The concept of the GSCM covers all the phases of a product’s life cycle, from the extraction of raw materials through the design, production and distribution phases, to the use of products by consumers.
and their disposal at the end of the product’s life cycle including reconditioning, reuse, and recycling of products.

Products and materials are returned from customers to suppliers and manufacturers through the reverse supply chain in order to be recycled, reused or reconditioned. Gungor and Gupta (1999) indicate that effort must be made for environmentally conscious manufacturing and product recovery systems to be profitable so that the incentive for development and planning of these systems continues. Then, it is required to establish a method for reconditioning, reuse, and recycling of used products efficiently and effectively in consideration of the feasibility of realizing a balance between environmental and economic concerns.

This study proposes a basic closed-loop supply chain model for parts reuse in consideration of economic efficiency. A new model component, a remanufacturer, is added to the previous model in order to represent the negotiation protocol among the organizations in the closed-loop supply chain. The remanufacturer collects used products from clients and provides reusable parts to manufacturers. The remanufacturer as well as manufacturers and suppliers modify their schedules and negotiate with each other in order to determine suitable prices and delivery times of products. The remanufacturer sends orders for used products to clients and stimulates clients to discard products for reuse in order to create a balance between supply and demand of reusable parts. A simulation model is proposed to represent the closed-loop supply chain model consisting of four kinds of organizations: suppliers, manufacturers, clients, and remanufacturers. The model proposed here is a minimum model of the closed-loop supply chain. The effectiveness of the model and the negotiation protocol are verified through computational experiments.

The reminder of this paper is organized as follows. Section 2 reviews the previous supply chain models. Section 3 describes the new model considering the closed-loop supply chains and presents a negotiation protocol among the organizations in the closed-loop supply chains. Finally, Section 4 demonstrates experimental results.

2. Literature review

Over the past dozen years and so, a large number of supply chain models have been considered for make-to-stock (MTS) companies with product inventories. Lee et al. (1997) described the Bullwhip effect occurring in supply chains as the considerable increase of the order variability relative to the variability of buyers’ demand. Li and O’Brien (1999) focused on improving supply chain efficiency and effectiveness under four criteria, profit, lead-time performance, delivery promptness and waste elimination, instead of the cost alone. The model analyzed the supply chain performance at two levels, the level of supply chain strategic design problems and the level of individual operations decision problems. Ganeshan (1999) presented a near-optimal inventory-logistics cost minimizing model for a production/distribution network with multiple suppliers supplying a distribution center. The decisions in the model were made through a comprehensive distribution-based cost framework that includes the inventory, transportation, and transit components of the supply chain. Bhattacharjee and Ramesh (2000) presented a multi-period inventory and pricing model for a single product, where the product has a fixed life perishability for a certain number of periods. The profit maximization problem was modeled as a dynamic program. Gupta et al. (2000) utilized a framework of mid-term, multisite supply chain planning under demand uncertainty to safeguard against inventory depletion at the production sites and excessive shortage at the customer. Banerjee et al. (2001) examined the effects of two controlled partial shipment approaches within a single supplier, multiple customers supply chain network through a series of simulation experiments under different operating conditions, based on the number of customers and the variability of their order sizes. Ganeshan et al. (2001) indicated the impact of three inventory parameters - the forecast error, the mode of communication between echelons, and the re-planning frequency. Giannoccaro and Pontrandolfo (2002) proposed a model to coordinate inventory management in a supply chain made up of three stages. The model was developed based on Markov decision processes and reinforcement learning to simultaneously design the inventory reorder policies of all the supply chain stages. Kaihara and Fujii (2002) proposed a negotiation strategy with various methods such as multi-stage negotiation protocols and game theoretic approaches. The supply agents and the demand agents determine the quantities of the required products and the suitable prices based on the number of the inventories. Nishi et al. (2003) proposed the decentralized supply chain optimization method. The problems of the supply chain planning among multi-companies are solved based on the limited information and the augmented Lagrangian decomposition method. However, the product inventories in the supply chains require the various kinds of additional cost for transfer, control, warehouse, and safety stock.

Some researchers have proposed a supply chain model without the product inventories for MTO companies
In recent years there are a lot of literatures on a closed-loop supply chain which includes not only traditional forward supply chains for the generation of products but also reverse supply chains for the reuse of products. The existing literatures on the closed-loop supply chain involve studies on network design problems, product acquisition management, marketing-related issues, etc. (Llgin and Gupta, 2010). Design problems of closed-loop supply chain networks involve a high degree of uncertainty associated with quality and quantity of used products. Robust optimization, such as stochastic programming, is commonly used to deal with the uncertainty. However uncontrolled acquisition of used products results in excessive inventory levels or stock-outs due to insufficient used products. Marketing-related issues include the pricing of remanufactured products. Some researches develop game theory-based models to determine prices of remanufactured products.

3. Closed-loop supply chain model for remanufacturing-to-order

3.1 Concept

This study proposes a closed-loop supply chain model for both MTO companies in forward supply chains and remanufacturing-to-order companies in reverse supply chains. Figure 1 shows a basic configuration of a closed-loop supply chain. Model components in the reverse supply chain receive used products from customers and provide usable parts to assembly manufacturers and parts suppliers. The components are referred to as remanufacturers in this study. This study also proposes a negotiation protocol which synchronizes the demand of reusable parts and the supply of used products among the components in the closed-loop supply chain. A lot of used products become waste products in traditional recovery approaches, since the customers may discard products without consideration for reuse of the products whenever they want. In the proposed new protocol, remanufacturers create a balance between supply and
demand of reusable parts. When some usable parts are required by manufacturers, remanufacturers stimulate clients to discard products for reuse by indicating high required prices for used products to clients. On the other hand, when few usable parts are required by manufacturers, remanufacturers indicate low required prices to clients in order to discourage clients from discarding products. Then, the remanufacturers can increase the amount of reused products and reduce waste products which are not reused in reverse supply chains. Remanufacturers enter into a lot of contracts for usable parts with manufacturers and increase their profits.

3.2 Remanufacturer model
3.2.1 Basic functions

The basic closed-loop supply chain model consists of four model components, i.e., clients, manufacturers, suppliers, and remanufacturers, as shown in Fig. 2. Remanufacturers collect used products from clients and provide reusable parts to manufacturers. Remanufacturers have neither stock of usable parts nor used products. Remanufacturers generate orders for used products and send them to clients when the remanufacturers receive orders from manufacturers for usable parts included in the used products. After receiving offers for used products from clients, remanufacturers generate offers for usable parts and send them to manufacturers. Remanufacturers modify their schedules for disassembly and repair of products and negotiate with each other in order to determine suitable prices and delivery times of products.

The notations used in the paper are listed as follows:
s
\(\text{Number of remanufacturers } s = 1, 2...S\)

\[\text{pcr}_{s,n}^O\]

Required price of a used product for product \(NC_{p,n}\). It is included in an order sent from remanufacturer \(R_s\) to clients.

\[\text{pcc}_{p,n}^O\]

Required price of product \(NC_{p,n}\). It is included in an order sent from client \(C_p\) to manufacturers.

\[\text{dtr}_{s,h,n}^F\]

Possible delivery time of a usable part for product \(NC_{p,n}\). It is included in an offer sent from remanufacturer \(R_s\) to manufacturer \(M_h\).

\[\text{pcr}_{s,h,n}^F\]

Bid price of a usable part for product \(NC_{p,n}\). It is included in an offer sent from remanufacturer \(R_s\) to manufacturer \(M_h\).

\[\text{dtm}_{h,n}^O\]

Required delivery time of a part and a usable part for product \(NC_{p,n}\). It is included in an order sent from manufacturer \(M_h\) to remanufacturers. This order is also sent to suppliers at the same time.

3.2.2 Orders from remanufacturers to clients

A remanufacturer \(R_s\) generates a new order for a used product and sends the order to all clients in order to collect a used product, when a remanufacturer receives an order for a usable part from a manufacturer \(M_h\). The order for a used product includes information about the required price \(\text{pcr}_{s,n}^O\) of a used product. The required price is estimated on the required price \(\text{pcc}_{p,n}^O\) of a product from a client \(C_p\).

\[\text{pcr}_{s,n}^O = \text{pcc}_{p,n}^O \times \text{pr}_{s,n}\] (1)

where

\[\text{pr}_{s,n}\]

A factor related to a required price of a used product

3.2.3 Offers from remanufacturers to manufacturers

After receiving and accepting an offer of a used product from a client \(C_p\) as a suitable offer, the remanufacturer modifies the schedule for disassembly and repair of products. The remanufacturer generates an offer of the usable part to the manufacturer \(M_h\). The offer includes the possible delivery time and the bid price of the usable part. The possible delivery time \(\text{dtr}_{s,h,n}^F\) and the bid price \(\text{pcr}_{s,h,n}^F\) are determined by using the following equations based on the modified schedule in the remanufacturer.

\[\text{dtr}_{s,h,n}^F = \text{ctr}_{s,h,n}\] (2)

\[\text{pcr}_{s,h,n}^F = \text{tcr}_{s,h,n}^F + \text{rwr}_{s,h,n} + \text{pnr}_{s,h,n} + \sum_{g=1}^{G} \text{G}_{s,h,n}^g\] (3)

\[\text{tcr}_{s,h,n}^F = \text{dcr}_{s,h,n}^F + \text{rcr}_{s,h,n}^F + \text{ppr}_{s,h,n}\] (4)

\[\text{rcr}_{s,h,n}^F = \text{pcc}_{p,n}^O \times F(t) \times \text{cr}_{s,h,n}\] (5)

\[\text{ppr}_{s,h,n} = \text{pcr}_{s,n}^O\] (6)

\[\text{pnr}_{s,h,n} = \text{km}_{h,n} \times \max\{\text{dtr}_{s,h,n}^F - \text{dtm}_{h,n}^O, 0\}\] (7)

where

\[\text{ctr}_{s,h,n}\]

Completion time of a usable part recovered by remanufacturer \(R_s\)

\[\text{tcr}_{s,h,n}\]

Total cost of a usable part

\[\text{rwr}_{s,h,n}\]

Reward for a usable part required by remanufacturer \(R_s\)

\[\text{pnr}_{s,h,n}\]

Penalty charge due to delay of a usable part
Penalty charge due to delays in delivery times of contracted orders $g$ ($g=1,2, \ldots, G$), if the addition of a product for disassembly and repair causes their delays.

Disassembly cost of a usable part.

Repair cost of a usable part.

Purchase price of a used product.

Cumulative failure rate estimated based on the Weibull distribution (Weibull, 1939, 1951).

A factor related to a repair cost of usable part.

Penalty charge factor representing penalty charge per unit time.

Equation (2) means that the latest finishing time of the usable part in the schedule for disassembly and repair in the remanufacturer equals to the possible delivery time of the remanufacturer. Processing times in the schedule include the disassembly time and the repair time of usable parts. The repair time is estimated based on a period of time which the product have been used. Equation (3) means that the remanufacturer discounts the price of the usable part by the penalty charge $pnr_{s,h,n}$, if the delivery time of the usable part does not satisfy the requirement of the manufacturer. If the usable part is delivered prior to the other contracted usable parts and the delivery time of the other contracted usable parts are delayed due to the insertion of the ordered usable parts into the schedules, the manufacturer of the usable parts has to accept a higher price that includes the penalty charges for the other delayed usable parts. Equation (4) represents that the total cost for recovering a usable part from a used product is estimated on the disassembly cost, the repair cost, and the purchases cost of a used product. The repair cost is estimated based on a period of time which the product have been used, as shown in Eq. (5). The purchases cost is equal to the required price $pcr_{s,h,n}$ determined by the remanufacturer in this paper. Equation (7) means that the remanufacturer has to pay the penalty charge to the manufacturer if the usable part cannot be delivered to the manufacturer by the required delivery time.

### 3.3 Extension of client model

This study adds a new function to the client model for decision making of discarding the used products. The client can decide when the used products are discarded by using the following equation.

$$utc_{p',n'} \geq plc_{p',n'}$$  \hspace{1cm} (8)

where

- $utc_{p',n'}$: A period of time when a product has been used by client $C_p$.
- $plc_{p',n'}$: A life cycle of a product. In this study, it is estimated based on the Weibull distribution which is commonly used to model life data (Sano, 2008).

A client discards the products which have been used beyond their life cycles. The products are dealt with as wastes, if they are not able to be reused in the reverse supply chains. However, when the client receives an order for reuse of a used product from a remanufacturer, the client decides which product is provided with the remanufacturer by using the following equations.

$$mv_{p',n'} \geq rn$$  \hspace{1cm} (9)

$$mv_{p',n'} = \frac{pcr_{s,h,n}}{pcr_{s,h,n}} - \frac{pv_{p',n'} - dcc_{p',n'}}{pcr_{s,h,n}}$$  \hspace{1cm} (10)

where

- $mv_{p',n'}$: Motivation for providing a product to remanufacturers for reuse.
- $rn$: Random numbers.
- $pv_{p',n'}$: Product’s value which decreases with time of use of a product from the initial price (Sano, 2008). It is estimated based on the Weibull distribution (Weibull, 1939, 1951).
- $dcc_{p',n'}$: Cost for discarding a product by client $C_p$. 
The proposed closed-loop supply chain model balances the demand of reusable parts and the supply of used products. Remanufacturers stimulate clients providing products for reuse by indicating high required prices for used products even if the product doesn’t satisfy the condition of Eq. (8). As if the remanufacturers deal with a client like a virtual warehouse, the remanufacturers can increase the amount of reused products and reduce waste products which are not reused in reverse supply chains.

3.4 Negotiation protocol

Steps in the negotiation process among the manufacturer, the remanufacturer, and the client are as follows:

Step 1 A manufacturer $M_h$ generates a new order for a part and a usable part, and sends it to all suppliers and remanufacturers when a new product is required from a client $C_p$.

Step 2 After receiving the order from manufacturer $M_h$, the remanufacturer $R_s$ generates a new order for a used product and sends it to all clients. The order includes the requirement of a used product about the price determined by Eq. (1).

Step 3 The client specifies candidates for discarding products which satisfy the condition determined by Eq. (8), and discards some products in the candidates. The client $C_p'$ generates an offer of a used product which is selected by Eqs. (9) and (10). The offer includes information about the bid price for a used product.

Step 4 When the remanufacturer $R_s$ receives the offer, the remanufacturer improves a schedule by using a genetic algorithm (GA) after adding disassembly processes and repair processes of the used product to the existing schedule. Then, the remanufacturer generates an offer for a usable part and sends the offer to the manufacturer $M_h$. The offer includes information about a possible delivery time and a bid price for the usable part, as shown in Eqs. (2) and (3). However if the remanufacturer receives no offer from clients or the estimated profit of the remanufacturer is less than 0, the remanufacturer cancels the order sent from the manufacturer. The estimated profit $epf_{s,h,n}$ is calculated by the following equation.

$$epf_{s,h,n} = rwr_{s,h,n} - pnr_{s,h,n} + \sum_{g=1}^{G} \Delta pnr_{s,h,g}$$

Step 5 When the manufacturer $M_h$ receives offers from suppliers and remanufacturers, the manufacturer selects one offer which has the lowest bid price. Then, the manufacturer improves the production schedule by using a GA after adding manufacturing processes of the selected part to the existing production schedule and generates an offer for the client $C_p$.

This negotiation process is repeated among the client, the manufacturers, the suppliers, and the remanufacturers until the client accepts an offer from a manufacturer or cancels the order. If the client accepts an offer from a manufacturer, the manufacturer can enter into the contract with the supplier or the remanufacturer. In case where the remanufacturer is selected, the remanufacturer can enter into the contract with the client which has provided the used product.

4. Computational experiments

A prototype of a simulation system for the closed-loop supply chains has been developed in order to evaluate the effectiveness of the proposed model and negotiation protocol. The prototype system was developed using Windows-based networked computers (Intel Core 2 Duo E8500 3.16 GHz CPU with 1.99 GB of RAM) for ease of applicability to real organizations. Clients, manufacturers, suppliers, and remanufacturers were able to be implemented as agents on different computers. Computer experiments were carried out on the closed-loop supply chain model consisting of two suppliers, two manufacturers, a remanufacturer, and a client by using six computers, as shown in Fig. 3. It is assumed that the two manufacturers can generate the same product which is required by a client. One product needs one part as a major component which is received to a manufacturer from a supplier or a remanufacturer. The other parts as accessory components, such as bolts, nuts, and cables, are sufficiently stored in a manufacturer.

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4.1 Experimental results of proposed model

The first experiments were carried out for evaluating the performance of the proposed model. In the initial conditions, the suppliers and the manufacturers had job-shop type production schedules consisting of 5 manufacturing resources and 20 contracted parts, and 10 manufacturing resources and 20 contracted products, respectively (Lawrence, 1984). The remanufacturer also had a similar schedule with the schedules of the suppliers. Processing times of operations in the manufactures are randomly determined from the uniform distribution between 80 and 600 second. On the other hand, processing times of operations in the suppliers and the remanufacturer are randomly determined from the uniform distribution between 8 and 60 second. Each job take one of the values 1 and 1.5 as a penalty charge factor. 

The client continuously generated 100 new orders including required prices \( pcc_{p,n} \) and delivery times \( dtc_{p,n} \) estimated by using the following equations and sent them to the two manufacturers for about 6 hours in the experiments.

\[
pcc_{p,n} = (1 + a_{p,n}) \times tcm_{p,n} \quad (12)
\]

\[
dtc_{p,n} = otc_{p,n} + b_{p,n} \times \sum_{j=1}^{J} pt_{p,n,j} \quad (13)
\]

where

- \( a_{p,n} \) Price factor determined from the uniform distribution between 0.5 and 0.9
- \( tcm_{p,n} \) Estimated total cost, including material cost and production cost of product \( NC_{p,n} \)
- \( otc_{p,n} \) Ordering time of product \( NC_{p,n} \). It is determined based on simulation run time.
- \( b_{p,n} \) Delivery time factor determined from the uniform distribution between 3.0 and 5.0
- \( pt_{p,n,j} \) Processing time of \( j \)-th manufacturing operation of product \( NC_{p,n} \) by a manufacturer
The manufacturers generated orders and negotiated with the suppliers and the remanufacturer every 30 seconds of bidding time in order to make suitable offers for the client. Population size, crossover rate, and mutation rate of the GA were 30, 0.8, and 0.2, respectively.

Two cases of experiments were carried out by changing the value of parameter $pr_{rn}$ which was used to determine a required price of a used product in Eq. (1). It was set to 0.15 and 0.10 in case 1 and case 2, respectively. Ten experiments were carried out on each case. The experimental results are summarized in Table 1, 2, and 3. Table 1 shows the number of both the reused products and the waste products. About 53 % of used products were reused in the reverse supply chains. Table 2 represents the number of contracts which are completed among the components in the supply chains. The remanufacturer entered into more contracts with the manufacturers than the suppliers. Then, about 55 % of new products were generated from the reused products. Table 3 summarizes the profits of the manufacturers, the suppliers, and the remanufacturer. The remanufacturer obtained higher profit than the suppliers, since the contracts of the remanufacturer were more than the ones of the suppliers. The parameter $rcc$ means the ratio of contracted prices to required ones of initial orders.

### Table 1 Number of reused products in experiments with proposed model

| Case  | Number of reused products [av.] | Number of waste products [av.] | Rate of reuse [av.] (%) |
|-------|--------------------------------|-------------------------------|------------------------|
| 1     | 43.2                           | 37.7                          | 53.4                   |
| 2     | 42.5                           | 37.3                          | 53.3                   |

### Table 2 Number of contracts in experiments with proposed model

| Number of contracts [av.] | Manufactures | Suppliers | Remanufacture | Sum of additional products (parts) [av.] |
|---------------------------|--------------|-----------|---------------|----------------------------------------|
|                           | $M_1$ | $M_2$ | $S_1$ | $S_2$ | $R_1$ |                                    |
| Case 1                    | 39.6  | 39.5   | 17.5  | 18.4  | 43.2  | 79.1                                |
| Case 2                    | 39.4  | 37.7   | 17.7  | 16.9  | 42.5  | 77.1                                |

### Table 3 Profit in experiments with proposed model

| Profit [av.] ($\times 10^3$ $\$) | Manufactures | Suppliers | Remanufacture | $rcc$ [av.] (%) |
|-----------------------------------|--------------|-----------|---------------|----------------|
|                                  | $M_1$ | $M_2$ | $S_1$ | $S_2$ | $R_1$ |                                    |
| Case 1                           | 279.9 | 279.7 | 55.4  | 56.1  | 89.7  | 79.2                                |
| Case 2                           | 278.2 | 259.0 | 53.1  | 53.4  | 76.2  | 80.2                                |

### 4.2 Comparison with conventional model

The second experiments were carried out in order to evaluate the effectiveness of the proposed model. Experimental results of the proposed model were compared with ones of a conventional model. In the conventional model, the client takes the initiative in discarding products. The client firstly determines which products are unnecessary by using Eq. (8). Then, remanufacturers can select products for reuse from the unnecessary products by using Eq. (9).

Ten experiments of the conventional model were carried out on each of two cases. The experimental conditions are the same as those of the first experiments described in section 4.1 except the decision making processes for the selection of reusable products. The experimental results of the conventional model are summarized in Table 4, 5, and 6. The number of reused products, the number of contracts, and the profits of organizations in the closed-loop supply chains are represented in Table 4, 5, and 6, respectively.

Figure 4 and 5 show the comparison of the experimental results of the proposed model with the ones of the conventional model from the viewpoints of the number of products used by the client and the number of parts used for products by the manufacturers, respectively. As shown in Fig. 4, the remanufacturer in the proposed model can...
decrease the amount of waste products and increase the reused products more than the one in the conventional model. The manufacturers in the proposed model can decrease the amount of new parts provided with the suppliers and increase the amount of reused parts provided with the remanufacturer more than the one in the conventional model, as shown in Fig. 5. Then, the remanufacturer in the proposed model obtained higher profit than the one in the conventional model. On the other hand, the suppliers in the proposed model obtained less profit than the ones in the conventional model. However there is little difference in profits of manufacturers between the proposed model and the conventional model. The client can obtain new products with similar prices regardless of the models, since the values of rcc are less different between the proposed model and the conventional model, as shown in Table 3 and 6.

| Case  | Number of reused products [av.] | Number of waste products [av.] | Rate of reuse [av.] (%) |
|-------|-------------------------------|-------------------------------|------------------------|
| Case 1| 5.7                           | 50.2                          | 10.2                   |
| Case 2| 12.7                          | 45.7                          | 21.9                   |

| Case 1 | Manufacturers | Suppliers | Remanufacture | Sum of additional products (parts) [av.] |
|--------|---------------|-----------|---------------|-----------------------------------------|
|        | M_1           | M_2       | S_1           | S_2           | R_1           | Sum          |
| Case 1 | 36.2          | 36.7      | 32.9          | 34.3          | 5.7           | 72.9         |
| Case 2 | 36.5          | 37.8      | 30.8          | 30.8          | 12.7          | 74.3         |

| Case 1 | Manufacturers | Suppliers | Remanufacture | rcc [av.] (%) |
|--------|---------------|-----------|---------------|---------------|
|        | M_1           | M_2       | S_1           | S_2           | R_1           | rcc [av.] (%) |
| Case 1 | 256.7         | 265.2     | 77.2          | 79.2          | 40.7          | 79.4         |
| Case 2 | 259.9         | 265.2     | 73.1          | 75.5          | 44.8          | 80.7         |

4.3 Simulation for reuse planning

This prototype of a simulation system can be used for the organizations in the closed-loop supply chains to make effective plans for reuse of products in consideration of economic efficiency. In this paper, about one hundred experiments were carried out on twenty-five experimental conditions by changing the values of parameters $cr_{sa}$ and $pr_{sa}$ which was used to determine a repair cost of a usable part and a required price of a used product, respectively.
Figure 6 describes the least squares approximation of the rate of reuse which has been derived from the experimental results. As shown in this figure, the reused parts with high repair costs decrease the rate of reuse. Not only the products purchased at low prices but also the ones purchased at high prices decrease the rate of reuse, since the client cannot provide the used products at lower prices than the product’s value and the manufacturer cannot enter into a contract with the remanufacturer at higher price than the price which the manufacturer requires.

5. Conclusion

This study proposes a basic closed-loop supply chain model consisting of suppliers, manufacturers, remanufacturers, and clients, as a minimum model for the closed-loop supply chains. It also proposes a negotiation protocol among the organizations in the closed-loop supply chains. A prototype of a simulation system has been developed to evaluate the effectiveness of the model and protocol. The proposed model was compared with a conventional model which discarded the used products without negotiation processes between remanufacturers and clients. The experiment results show that the proposed model can reuse products about 40% more than the conventional model. The prototype system can be used for reuse planning considering economic efficiency.

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