Int J Adv Manuf Technol (2008) 39:1197–1206
DOI 10.1007/s00170-007-1290-7

ORIGINAL ARTICLE

A mixed integer programming model for remanufacturing in reverse logistics environment

Neslihan Özgün Demirel · Hadi Gökçen

Received: 13 June 2007 / Accepted: 15 October 2007 / Published online: 29 January 2008

Abstract Recently, there has been a growing interest in reverse logistics due to environmental deterioration. Firms incorporate reverse flow to their systems for such reasons as ecological and economic factors, government regulations and social responsibilities. In this paper a new mixed integer mathematical model for a remanufacturing system, which includes both forward and reverse flows, is proposed and illustrated on a numerical example. The proposed model provides the optimal values of production and transportation quantities of manufactured and remanufactured products while solving the location problem of dissassembly, collection and distribution facilities. The model is validated by using a set of experimental data reflecting practical business situation. Sensitivity analysis of the model is also presented.

Keywords Integer programming · Product recovery · Remanufacturing · Reverse logistics

1 Introduction

Due to the increasing environmental concern, resource reduction, depleting landfill capacities in many countries and enacted obligations by governments to take back the end-of-life products, issues like reverse logistics, product recovery, remanufacturing, and reusing have received growing attention. Reverse logistics, which is one of these issues can be defined as a process that includes all logistics activities and starts from the point of consumer to transform the used products to products which are reusable in the market [1]. Reverse logistics activities can improve the competence of enterprises, customer service level, and reduce the production costs [2]. On the other hand, reverse logistics provides a green image to the firms by increasing the demand of conscious customers for their products.

In the past, because there were no regulations or public concern that pressured the companies to dispose of the product at the end of its life, firms thought that once the products left their warehouses, they were no longer their responsibility. Therefore, it is not surprising to see that most companies only put their effort in just designing a logistics network that efficiently moves the products from seller to buyer. This type of logistics network is referred to as *forward logistics network* [1, 3, 4]. However, this is no longer true. Firms have been edging toward new strategies to make profit or at least to survive under such competitive marketing conditions. One of these strategies is the use of *reverse logistics*. Unlike the traditional logistics, reverse logistics deals with the problem of how to retrieve products efficiently from the customers.

Recovery networks including collection of the used products from customers, *recovery of used products to take them into reusable condition and distribution to customers*, are quite different from traditional networks in many cases. Most researchers agree that forward logistics and reverse logistics have different characteristics and therefore one cannot just simply use their existing forward logistics network to handle the reverse flow [3].

Used products can be recovered in a variety of ways. These product recovery options can be classified as repairing, refurbishing, remanufacturing, cannibalization, and recycling [5]. The right option may be selected by taking the condition and age of the returned product and

N. Ö. Demirel (✉) · H. Gökçen
Faculty of Engineering and Architecture,
Department of Industrial Engineering, Gazi University,
Maltepe,
06570 Ankara, Turkey
e-mail: neslihanozgun@gazi.edu.tr

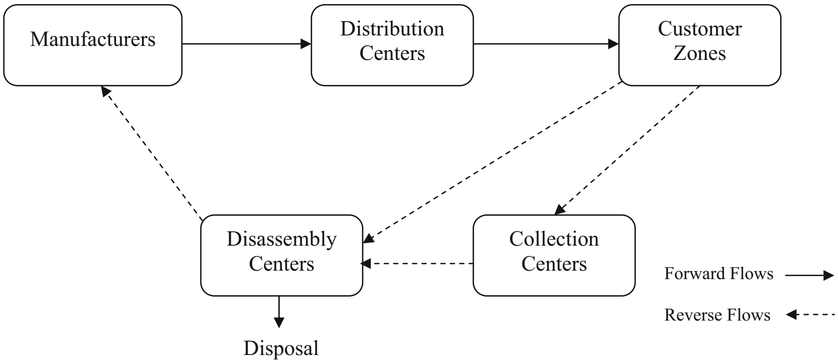

Fig. 1 A logistics network including forward and reverse flows for remanufacturing

economics into consideration [6]. Once firms choose the correct option they should use for recovery, they must decide the design of the reverse logistics network. There are a lot of reverse logistics network configurations depending on the recovery option and the type of the recovered product [2]. However, only a few researchers have focused on the development of a general framework and mathematical model about remanufacturing system [7]. The literature on reverse logistics is rather extensive. For literature on reverse logistics the review papers of [1, 8–10] can be seen.

In the literature, reverse logistics models can be classified as independent models and integrated models [2]. Only the reverse channel is considered in the case of the independent models whereas integrated models include both forward and reverse channels. It is well worth pointing out that more emphasis is given to the independent models as compared to the integrated models in the literature. The examples of independent models can be found in the references [11–15]. It has been recognized that although there are a lot of papers in the published literature on *modeling forward and reverse flows* independently, there are not as many necessary articles that provide an integrated approach. The examples of integrated models can be found in references [4, 16, 17] as well.

In this paper, a remanufacturing option which is environmentally friendly and profitable for product recovery is discussed. Remanufacturing is a product recovery option in which products (or parts and components) are restored to a condition having the same characteristics with the new product in terms of both quality and technical performance. To return the used product to this condition, disassembly and inspection processes must be performed. Worn out or outdated parts and modules are replaced and tested in the process of disassembly of the product. Technological upgrades may also be included [5]. A product is considered to be remanufactured if its primary components come from a used product (after ensuring that they are functional) [18]. Automobile parts, copiers, medical equipments, computer parts, tires, cartridge, office furniture, and more examples for remanufactured products can be given.

The studies related to remanufacturing have increased after the 1980s and there have been a lot of research studies conducted on the subject from the 1980s onward. Lund [19] defined remanufacturing as an industrial process in which worn out products are restored to the condition of a new product. Lund [19] also identified the categories of products that are frequently remanufactured. Amezquita et al. [20] attempted to characterize the remanufacturability of engineering systems. Guide [21] and Guide et al. [22] focused on the capacity planning for remanufacturing. Van der Laan et al. [23] studied the production and inventory planning activities for systems composed of manufactured and remanufactured products. Jayaraman et al. [13], Guide et al. [6], Seitz and Paettie [24], Georgiadis and Vlachos [25] discussed the unique characteristics of logistics network for remanufacturing. Although there are a lot of studies on various spesific areas of remanufacturing, only a few research studies have focused on the development of a general framework and mathematical model about remanufacturing system [7]. In order to fill this gap in the literature, in this work we focused on the design of a generic framework of a remanufacturing system (which includes forward and reverse flows together) along with the development of an analytic model. The model is validated by using a set of experimental data representing the practical business situation and sensitivity analysis of the model is also presented.

2 Proposed model

In reverse logistics, how to integrate the forward and reverse channels is an important decision making point. In order to design an efficient reverse logistics channel, firms must determine which elements and functions should exist in logistics network and where these elements and functions should be actualized, how relations between forward and reverse channels should come about [26].

In this section a mixed integer mathematical model is presented in which forward and reverse flows and their mutual interactions are considered simultaneously (integrated model).

The proposed model provides optimal values of production and transportation quantities of manufactured and remanufactured products and solves the location problem of dissassembly, collection and distribution centers.

In the proposed model we dealt with disassembly costs for a certain fraction of the collected products that were appropriate for recovery and disposal costs for the remaining fraction of the collected products. We also incorporated collection costs of end-of-life products from customers to the model. The objective of the proposed model is to minimize the total cost of the system including production, transportation, collection, purchasing, disassembly, and disposal costs.

The remanufacturing system discussed here can be conceptualized into a framework as shown in Fig. 1. In the presented network manufactured products are initially transported to distribution centers and to customer zones from there as a forward flow. Reverse flow starts with the collection of the used products from customers. The used products in the customer zones are sent to the chain for several reasons such as lack of satisfying quality specifications or being defective. It is assumed that a certain amount of used products, defined as a percentage of demand must be collected in customer zones. Each customer zone has a known demand that must be satisfied and all returned products must be collected from customer zones. The used products can be transported to disassembly centers through collection centers or if it is more profitable they will be directly shipped to disassembly centers from customer zones. The products returned to the disassembly centers are revised, classified and organized by the disposal and remanufacturing strategy. Returned products which are of good quality for remanufacturing can be disassembled and processed until they become parts and/or components. Remanufacturing process generally involves total disassembly and extensive inspection of all parts and modules. When the product has been disassembled, parts/components are cleaned and tested. Just like assembly lines, which are used to assemble components into a final product which has high volume [27], disassembly lines are essential to transform the discarded products to parts/components. Recovery process is performed on the parts to provide them with the same conditions as the new ones. 'New' parts are transported to manufacturing facilities and used for manufacturing products.

There are two ways for a company to supply parts. One is purchasing the required parts from external suppliers; and the other is acquiring them by disassembling and reprocessing the used products which are in good condition for remanufacturing. To minimize the total costs of the system, the company must decide on the number of products to be disassembled and the parts to be purchased from suppliers. The transported quantities of new and used products and collected and disposed quantities of used products must be optimized in order to determine the total cost of the remanufacturing system. The mixed integer mathematical model which provides all of the above mentioned decisions and its formulation are presented below.

2.1 Formulation of the model

- Indices

i	product
k	manufacturer
l	distribution center
n	collection center
m	customer zone
p	disassembly center

- Parameters

f_p	opening cost of disassembly center p.
f_l	opening cost of distribution center l.
f_n	opening cost of collection center n.
t_i	transportation cost of one unit of product i per mile.
a_i	quantity of part/component obtained from one unit of product i.
DC_i	disposal cost per unit of product i (assumed to be the same for all disassembly centers).
CC_i	collection cost per unit of product i (assumed to be the same for all collection centers).
CAP_k	holding capacity of part/component in manufacturer k
TD_i	total demand of product i.
s_i	returned fraction of the demand from customer zones for product i.
b_i	fraction of returned product i satisfying the quality specifications for remanufacturing.
D_{im}	demand of customer zone m for product i.
c_{ik}	production cost per unit of product i in manufacturer k.
d_{ip}	disassembly cost per unit of product i in disassembly center p.
CAP_{ik}	production capacity of product i in manufacturer k.
CAP_{ip}	disassembly capacity of product i in disassembly center p.
CAP_{in}	collection capacity of product i in collection center n.
CAP_{il}	distribution capacity of product i in distribution center l.
b_{kl}	the distance between manufacturer k and distribution center l.
b_{lm}	the distance between distribution center l and customer zone m.
b_{np}	the distance between collection center n and disassembly center p.
b_{pk}	the distance between disassembly center p and manufacturer k.

Table 1 Product information

Products	Transportation costs (per unit)	Collection costs (per unit)	Disposal costs (per unit)	Part amount obtained from one product	Return rates	Acceptation rates
Product 1	0.02	0.5	2	3	0.20	0.20
Product 2	0.01	1	1	3	0.10	0.40

b_{mp}	the distance between customer zone m and disassembly center p.
b_{mn}	the distance between customer zone m and collection center n.
TC	transportation cost for one unit of part/component per mile.
PC	purchasing cost per unit of part/component.

- Decision Variables

x_{ikl}	quantity of product i shipped to distribution center l from manufacturer k.
x_{ilm}	quantity of product i shipped to customer zone m from distribution center l.
x_{imn}	quantity of product i shipped to collection center n from customer zone m.
x_{inp}	quantity of product i shipped to disassembly center p from collection center n.
x_{ipk}	quantity of product i shipped to manufacturer k from disassembly center p.
x_{imp}	quantity of product i shipped to disassembly center p from customer zone m.
x_{pk}	quantity of component shipped to manufacturer k from disassembly center p.
q_{ik}	number of units of product i produced in manufacturer k.
Q_k	number of units of part/component purchased from an external supplier to manufacturer k.
y_p	the indicator of opening disassembly center p.
y_l	the indicator of opening distribution center l.
y_n	the indicator of opening collection center n.

Bu using the incides and parameters above, the model for remanufacturing system is formulated as follows:

Objective function

Min

$$
\begin{aligned}
&\sum_p f_p \cdot y_p + \sum_l f_l \cdot y_l + \sum_n f_n \cdot y_n + && \textit{Opening costs}\\
&\sum_i \sum_k c_{ik} \cdot q_{ik} + && \textit{Production costs}\\
&\sum_i \sum_k \sum_l t_i \cdot x_{ikl} \cdot b_{kl} + \sum_i \sum_l \sum_m t_i \cdot x_{ilm} \cdot b_{lm} + \sum_i \sum_m \sum_n t_i \cdot x_{imn} \cdot b_{mn} + && \\
&\sum_i \sum_n \sum_p t_i \cdot x_{inp} \cdot b_{np} + \sum_i \sum_m \sum_p t_i \cdot x_{imp} \cdot b_{mp} + && \textit{Transportation costs of products}\\
&\sum_p \sum_k t \cdot x_{pk} \cdot b_{pk} + && \textit{Transportation costs of components}\\
&\sum_i \sum_p b_i \cdot s_i \cdot d_{ip} \cdot TD_i + && \textit{Disassembly costs}\\
&\sum_i (1 - b_i) \cdot s_i \cdot DC_i \cdot TD_i + && \textit{Disposal costs}\\
&\sum_i s_i \cdot CC_i \cdot TD_i + && \textit{Collection costs}\\
&PC \cdot \sum_k Q_k && \textit{Purchasing costs}
\end{aligned} \tag{1}
$$

Table 2 Production costs per unit

Manufacturers	Products	
	Product 1	Product 2
k1	180	120
k2	140	110
k3	150	100

Table 3 Disassembly costs per unit

Disassembly Centers	Products	
	Product 1	Product 2
p1	8	2
p2	5	3

Table 4 Produced quantities in manufacturers

Products	Manufacturers		
	k1	k2	k3
Product 1	500	1000	1700
Product 2	100	2100	1500

Constraints

$$q_{ik} \leq CAP_{ik} \qquad \forall i,k \tag{2}$$

$$q_{ik} = \sum_{l} x_{ikl} \qquad \forall i,k \tag{3}$$

$$\sum_{l} x_{ilm} = D_{im} \qquad \forall i,m \tag{4}$$

$$\sum_{n} x_{imn} + \sum_{p} x_{imp} = s_i \cdot \sum_{l} x_{ilm} \qquad \forall i,m \tag{5}$$

$$\sum_{k} x_{pk} = \sum_{i}\sum_{m} x_{imp} \cdot b_i \cdot a_i + \sum_{i}\sum_{n} x_{inp} \cdot b_i \cdot a_i \quad \forall p \tag{6}$$

$$\sum_{k} x_{ikl} = \sum_{m} x_{ilm} \qquad \forall i,l \tag{7}$$

$$\sum_{m} x_{imn} = \sum_{p} x_{inp} \qquad \forall i,n \tag{8}$$

Table 5 Transported quantities from customer zones to collection centers

Customer zones	Collection centers			
	n1		n2	
	Product 1	Product 2	Product 1	Product 2
m1	110	20		
m2	200	150		
m3	290	120		

Table 6 Transported quantities directly from customer zones to disassembly centers

Customer zones	Disassembly centers			
	p1		p2	
	Product 1	Product 2	Product 1	Product 2
m1			40	80
m2				

$$\sum_{n} x_{inp} + \sum_{m} x_{imp} \leq CAP_{ip} \cdot y_p \qquad \forall i,p \tag{9}$$

$$Q_k + \sum_{p} x_{pk} \leq CAP_k \qquad \forall k \tag{10}$$

$$\sum_{k} x_{ikl} \leq CAP_{il} \cdot y_l \qquad \forall i,l \tag{11}$$

$$\sum_{m} x_{imn} \leq CAP_{in}.y_n \qquad \forall i,n \tag{12}$$

$$\sum_{i} q_{ik} \cdot a_i = Q_k + \sum_{p} x_{pk} \qquad \forall k \tag{13}$$

$$TD_i = \sum_{m} D_{im} \qquad \forall i \tag{14}$$

$$x_{ikl}, x_{ilm}, x_{imn}, x_{inp}, x_{imp}, x_{pk}, q_{ik}, Q_k \leq 0 \text{ and integer} \tag{15}$$

$$y_n, y_1, y_p \in \{0,1\} \tag{16}$$

The objective of the model shown in (1) is to minimize the overall costs of the system. Constraint (2) stipulates that the production quantity of each product must not exceed the production capacity of that manufacturing facility. Constraint (3) requires total outgoing flows from each manufacturer

Table 7 Part quantities transported from disassembly centers to manufacturers

Disassembly centers	Manufacturers		
	k1	k2	k3
p1	168		
p2			660

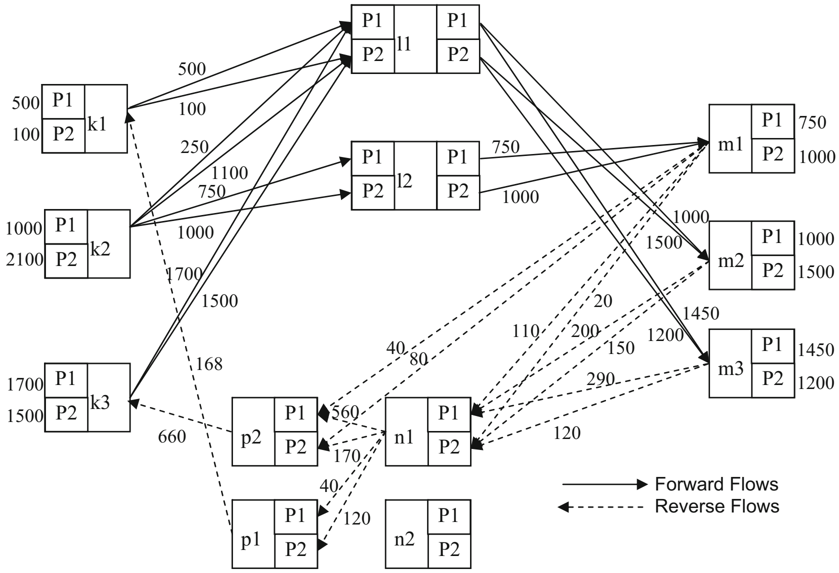

Fig. 2 Optimal results for illustrative example (P1-product 1, P2-product 2)

should be as big as the quantity of manufactured products. Constraint (4) ensures that demands for each product must fully be met. Constraint (5) is the flow constraint balancing the quantities of returned products. Constraints (6), (7), and (8) are the balance equations for the disassembly, distribution, and collection centers: the quantities that enter to these facilities must be equal to the amount of products/parts that leave the facilities. Constraint (9) is the constraint ensuring that the quantities distributed to disassembly center cannot exceed the capacity in the event that the disassembly facility is opened. Constraint (10) is the existing capacity constraint of manufacturers for parts/components. Constraint (11) and (12) restrict the capacity of distribution and collection centers. Constraint (13) provides the required quantities of parts/components for manufacturing. Constraint (14) indicates that total demand of each product is equal to all customer zones' demands for that product. Constraint (15) enforces the non-negativity restriction on the decision variables. Lastly constraint (16) represents the binary variables.

3 Illustrative example

The model is illustrated through an example in this section. A small set of parameters reflecting a real-life industrial case is selected for the example. A recovery network is formulated as a mixed-integer mathematical model for multi-product (two products) in order to find the optimal values of the quantities between sites and also, in order to determine which disassembly, distribution, and collection centers should be opened. The network includes three manufacturers (k1,k2,k3), two potential distribution centers (l1,l2), two potential collection centers (n1,n2), two potential disassembly centers (p1,p2), and three customer zones (m1,m2,m3). The model is solved by using GAMS-CPLEX solver on a Pentium IV 3 GHz personal computer for the parameters presented in Tables 1, 2 and 3, with the intention of obtaining optimal values. The information on two products including transportation costs, collection costs, return rates, etc., is given in Table 1. The production costs of manufacturing facilities and disassembly costs of disassembly centers for each product are also given in Tables 2 and 3. Opening costs of the potential facilities are determined as; 20000, 25000, 10000, 7500, 6000 and 8000 for p1, p2, l1, l2, n1 and n2, respectively. The demands of customer zones for each individual product are set to be 750, 1000, 1450 for product 1 and 1000, 1500, 1200 for product 2. Capacities of facilities are considered to be restricted for each individual product type to reflect the real life situation. For this reason the capacities of manufacturers are determined as 2750, 1000, 1700 for product 1, and 1800, 2100, 1500 for product 2. Capacities of the disassembly, collection and distribution centers are also

Table 8 Parameter intervals used in generating random problems

Parameter	Interval
Transportation costs	0,01–0,05
Collection costs	0,5–5
Disposal costs	1–5
Disassembly costs	5–10
Production costs	250–300
Opening costs of distribution centers	15000–25000
Opening costs of collection centers	8000–15000
Opening costs of disassembly centers	20000–30000
Demands	100–200
Distances	100–1000

Table 9 Optimization results for low rate of returns (scenario 1)

m	l	k	i	n	p	Return rate	Total cost	CPU time(sec.)
3	2	3	2	2	2	0.2	479813	0.05
5	2	3	2	2	2	0.1	745607	0.05
10	2	3	2	2	2	0.1	1489248	0.13
10	5	10	2	5	5	0.2	1372717	0.25
15	5	10	2	5	5	0.2	2138904	0.64
20	5	10	3	5	5	0.1	4413937	1.55
25	10	10	3	7	7	0.2	5334610	1.22
25	10	15	3	7	7	0.1	5241540	8.39
30	10	15	3	7	7	0.2	6178810	7.89
40	10	15	5	10	10	0.1	14030022	196.72
50	20	25	5	10	10	0.1	17451863	133.78
70	25	30	10	15	15	0.2	48099878	3661.25
100	30	30	15	20	20	0.2	104677843	3691.69
150	30	30	15	20	20	0.1	156004372	3721.05
200	30	30	15	20	20	0.1	209030911	3719.45
250	30	30	30	30	30	0.2	531071233	4871.61

determined with similar sense but not shown here. Other relevant data such as the distances between facilities are also generated for the proposed model.

When the proposed model is solved for the given example, total cost is found out to be 1,149,870. Two of the potential distribution and disassembly centers and only the first one of the collection centers are opened in the optimal solution. Quantity of components purchased to manufacturer 1, 2, and 3 are determined as 1632, 9300, and 8940, respectively. The experimental results for the remanufacturing system example are given in Tables 4, 5, 6, and 7. The optimal results are also illustrated in Fig. 2. The produced quantities of each product type in manufacturers along with the transported quantities between sites in the optimal solution and also, demands of customer zones for each product can also be seen in Fig. 2.

Table 4 shows the produced quantities in manufacturing centers by using new parts purchased from external suppliers or recovered parts received from disassembly centers. Note that a major amount of the production is carried out in manufacturing centers 2 and 3 due to the high unit production costs in the first manufacturer.

If used products are no longer benefical to their users, some of them are incorporated to the chain to satisfy the government regulations or customer expectations and/or to make profit. Table 5 shows the returned product quantities

Table 10 Optimization results for medium rate of returns (scenario 2)

m	l	k	i	n	p	Return rate	Total cost	CPU time(sec.)
3	2	3	2	2	2	0.3	474685	0.05
5	2	3	2	2	2	0.4	715184	0.05
10	2	3	2	2	2	0.3	1458312	44.78
10	5	10	2	5	5	0.6	1314278	75.44
15	5	10	2	5	5	0.5	2014057	103.66
20	5	10	3	5	5	0.5	3893802	101.55
25	10	10	3	7	7	0.4	4974592	114.83
25	10	15	3	7	7	0.6	5105639	135.39
30	10	15	3	7	7	0.3	6172446	97.63
40	10	15	5	10	10	0.5	13198018	243.92
50	20	25	5	10	10	0.4	16980648	511.05
70	25	30	10	15	15	0.6	46750271	2999.84
100	30	30	15	20	20	0.5	103063477	3896.50
150	30	30	15	20	20	0.4	155870282	3937.52
200	30	30	15	20	20	0.3	207643424	3686.55
250	30	30	30	30	30	0.6	554453162	3969.88

Table 11 Optimization results for high rate of returns (scenario 3)

m	l	k	i	n	p	Return rate	Total cost	CPU time(sec.)
3	2	3	2	2	2	1.0	459670	0.05
5	2	3	2	2	2	0.9	668980	0.05
10	2	3	2	2	2	1.0	1212851	176.38
10	5	10	2	5	5	0.8	1273275	175.14
15	5	10	2	5	5	0.7	1979509	201.28
20	5	10	3	5	5	0.9	3808642	203.03
25	10	10	3	7	7	0.7	4791210	205.77
25	10	15	3	7	7	1.0	4828358	180.95
30	10	15	3	7	7	0.8	5869585	154.25
40	10	15	5	10	10	0.8	12657047	203.36
50	20	25	5	10	10	1.0	15306813	400.66
70	25	30	10	15	15	0.9	46141454	3619.72
100	30	30	15	20	20	0.7	103248093	3738.72
150	30	30	15	20	20	0.7	154662704	3640.17
200	30	30	15	20	20	0.8	205281908	3665.64
250	30	30	30	30	30	0.7	562578950	4087.44

m: customer zones
i: products
l: distribution centers
n: collection centers
k: manufacturers

that are collected in collection centers. Since it is a strategic planning problem, it is assumed that the returned product quantities are dependent on demand and known before. So, we treated the returned product quantities as a percentage of demand. It is easily noticed that the end-of-life products are never transported to collection center 2 in the optimal solution. This is because the model decided not to open the second collection center. End-of-life products can be collected in collection centers or disassembly centers. If transporting returned products from customer zones to disassembly centers is more profitable, the model permits to ship them directly to disassembly centers without visiting collection centers. In practice being a major part of the total costs, transportation cost is one of the main factors influencing transportation decisions of the firms. Quantities transported from customer zones directly to disassembly centers are given in Table 6. The used products which have been tested in terms of quality are disassembled and thus, parts that are to be used in remanufacturing are obtained. These parts go through some recoveries such as cleaning, and they achieve the characteristics of new ones. Parts having the same characteristics with the new ones are then sent to the manufacturers to be used in production. In Table 7, the amounts of these sent parts are presented. Note that the total amount of parts transported from disassembly centers to manufacturing centers is dependent on the transported product quantities to there and the quality of them. For example, in the case of disassembly center 1, since the transported quantities from collection centers are 40 for product 1 and 120 for product 2 (can be seen in Fig. 2), and the acceptation rates of products are 0.20 and 0.40 and part amount received from one product is 3 (can be seen in Table 1), the total amount of transported components must be equal to $(40*0.20+120*0.40)*3=168$. This value is the same with the value of shipped part quantity from disassembly center 1 in Fig. 2.

4 Experimental design and analysis

Numerical experiments have been carried out in order to test the behavior of the proposed model under large scale problems. The parameters are varied in the above example over a large range. A set of 300 different problems with the same input data structure are solved to achieve a reasonable level of confidence about the performance and validation of the solution procedure and results of some of them are shown here. Parameter intervals used in producing random problems for experimental analysis can be seen in Table 8.

In order to study the sensitivity of the proposed model to the relative values of the data, each problem size is resolved for different values of return rates (0.1–1) and three different scenarios are considered including low, medium and high rates of returns of each product. Scenarios are defined in terms of the percentage of returns. For the first scenario, a low rate of returns is considered. It is assumed that 10%–20% of demand returns to the chain in this scenario. For the second scenario, the returning rate is assumed to be 30%–60%. The third scenario considers a high rate of returns, and a product return of 70%–100% of the demand is considered.

Some of various examples, varying the number of manufacturing plants, customer zones, product types, distribution, collection, and disassembly centers under three different scenarios can be seen in Tables 9, 10, and 11.

In Tables 9, 10, and 11 l,*n, and p columns* represent the maximum numbers of potential facilities that can be opened. For example, in Table 11, for the largest problem size there are 11 opened disassembly centers of 30, and 23 opened collection centers of 30 in the optimal solution. The proposed model decided to open all of the distribution centers for this example.

It can be clearly understood from the results that when problem size increases, the time required to solve the problem and total cost of the system generally increase, and when return rates increase, total cost of the remanufacturing system decreases for the same problem sizes. For example, for the first problem size including 3 customers, 2 distribution centers, 3 manufacturers, 2 collection centers, 2 disassembly centers, and 2 products for low rate of returns (scenario 1), total cost of the system is 479,813; whereas for medium rate of returns (scenario 2), the cost is determined as 474,685. Finally, in the case of high rate of returns (scenario 3), total cost of the system is decreased to 459,670.

In the case of high return rates, these cost savings can be seen in almost all problem sizes. Total cost of the remanufacturing system increases with increasing return rates only for very large problem sizes with 250 customer zones, and 30 product types because each customer zone has a demand for each product and all facilities have finite capacities, so the system requires more opened facilities concluded with increasing fixed costs.

5 Conclusion

In this paper, a general recovery network is designed in that it can meet different industries' requirements and a mixed-integer programming model is developed for the remanufacturing systems which includes *multi-phase and multi-product* forward and reverse distribution. The proposed model is illustrated through an example by using a set of data reflecting a real life business situation. Different large-scale problems are solved within an experimental design scheme in order to validate the performance and sensitivity of the proposed model. Three different scenarios; *with a low, medium, and high rate of returns* have been established in order to compare the possible performance of different scenarios and to allow the plan maker to take a better decision as well. Therefore, a unique tool is provided so as to understand how the system behaves under different rate of returns.

It can be concluded from the obtained results that companies should provide suitable incentives to customers, retailers and/or subcontracters to take back more *used products*. Thus, they will improve their competitiveness as well as become more environmentally friendly and they will almost always be able to receive more profit.

For practical purposes and future research, due to exponentially increasing time with increasing problem sizes, a heuristic procedure to solve the mixed-integer programming model in a reasonable time needs to be developed.

References

1. Fleischmann M, Bloemhof-Ruwaard JM, Dekker R, van der Laan E, van Nunen JAEE, van Wassenhove LN (1997) Quantitive models for reverse logistics: a review. Eur J Oper Res 103(1):1–17
2. Dolgui A, Soldek J, Zaikin O (2005) Supply chain optimization product/process design, facility locatýon and flow control, 94. Springer, Boston
3. Timben-Lemke RS, Rogers DS (2002) Differences between forward and reverse logistics in a retail environment. Supply Chain Managemen:Int J 7(5):271–282
4. Fleischmann M, Beullens P, Bloemhof-Ruwaard JM, van Wassenhove LN (2001) The impact of product recovery on logistics network design. Prod Oper Manag 10(2):156–173
5. Thierry M, Salomon M, Van Nunen J, Van Waasenhove L (1995) Strategic issues in product recovery management. Calif Manage Rev 37(2):114–135
6. Guide Jr. VD, Jayaraman V, Srivastava R, Benton WC (2000) Supply chain management for recoverable manufacturing systems. Interfaces 30(3):125–142
7. Kim K, Song I, Kim J, Jeong B (2006) Supply planning model for remanufacturing system in reverse logistics environment. Comput Ind Eng 51:279–287
8. Guide Jr. VD, Jayaraman V (2000) Product acquisition Management: current industry practice and a proposed network. Int J Prod Res 38(16):3779–3800
9. Dowlatshahi S (2000) Developing a theory of reverse logistics. Interfaces 30(3):143–155
10. Rogers DL, Tibben-Lemke RS (2001) An examination of reverse logistics practices. J Bus Logist 22(2):129–148
11. Barros AI, Dekker R, Scholten V (1998) A two-level network for recycling sand: a case Study. Eur J Oper Res 110:199–214
12. Louwers D, Kip BJ, Peters E, Souren F, Flapper SDP (1999) A facility location allocation model for reusing carpet materials. Comput Ind Eng 36:855–869
13. Jayaraman V, Guide Jr. VD, Srivastava R (1999) A closed loop logistics model for remanufacturing. J Oper Res Soc 50(5):497–508
14. Shih L (2001) Reverse logistics system planning for recycling electrical appliances and computers in Taiwan, Resources. Conserv Recycl 32:55–72
15. Spengler Th, Püchert H, Penkuhn T, Rentz O (1997) Environmental integrated production and recycling management. Eur J Oper Res 97:308–326
16. Bloemhof-Ruwaard JM, Salomon M, Van Wassenhove LN (1996) The capacitated distribution and waste disposal problem. Eur J Oper Res 88:490–503
17. Marín A, Pelegrín B (1998) The return plant location problem: modeling and resolution. Eur J Oper Res 104:375–392

18. Majumder P, Groenevelt H (2001) Competition in remanufacturing. Prod Oper Manage 10(2):125–141
19. Lund R (1983) Remanufacturing: United States Experience and implications for developing nations. World Bank, Washington DC
20. Amezquita HA, Bras BA, Hammond RC, Salazar M (1995) Characterizing the remanufacturability of engineering systems. Proc 1995 ASME Advances in Design Automation Conference. Boston, Massachusetts, pp 271–278, 17-20 September
21. Guide Jr VD (1994) Rough cut capacity planning for remanufacturing firms. Air Force Institude of Technology, AFIT-LA-TM-942
22. Guide Jr VD, Srivastava R, Spencer M (1997) An evaluation of capacity planning techniques in a remanufacturing environment. Int J Prod Res 35(1):67–82
23. Van der Laan E, Salomon M, Dekker R (1995) Production planning and inventory control for remanufacturable durable products. Report 9531/A. Erasmus Univ, Rotterdam, The Netherlands
24. Seitz MA, Peattie K (2004) Meeting the closed-loop challenge: the case of remanufacturing. Calif Manage Rev 46(2):74–89
25. Georgiadis P, Vlachos D (2004) The Effect of environmental parameters on product recovery. Eur J Oper Res 157(2):449–464
26. Fleischmann M, Krikke HR, Dekker R, Flapper SDP (1999) Logistics network redesign for product recovery and reuse. Management Report Series 17, Erasmus Univ, Rotterdam, Netherlands
27. Gökçen H, Aðpak K (2006) A goal programming approach to simple U-line balancing problem. Eur J Oper Res 171:577–585