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Optimizing a reverse supply chain including transportation, operation, maintenance and remanufacturing costs

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Abstract Reverse supply chain is a process dealing with the backward flows of used/damaged products or materials. Reverse supply chain includes activities such as collection, inspection, reprocess, disposal and redistribution. A well-organized reverse supply chain can provide important advantages such as economic and environmental ones. In this study, we propose a general framework and formulate a mathematical model for product return in reverse supply chain. We consider a multi-layer, multi-product for the model. The main objective of the paper is minimizing the total costs of reverse supply chain including transportation, fixed opening, operation, maintenance and remanufacturing costs of centers. To validate the mathematical model, a numerical example is solved using Lingo 9 software and the results are reported.

Keywords Reverse Supply Chain, Product Return, Mathematical Model.

1 Introduction

With the increase in environmental consciousness, reverse supply chain and reverse supply chain management have received significant attention from both business and academic research during the past few years. According to the American Reverse Logistics Executive Council, Reverse Logistics is defined as Rogers and Tibben-Lembke [1]: "The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal." A reverse logistics system comprises a series of activities, which form a continuous process to treat return-products until they are properly recovered or disposed of. These activities include collection, cleaning, disassembly, test and sorting, storage, transport, and recovery operations. The latter can also be represented as one or a combination of several main recovery options, like reuse, repair, refurbishing, remanufacturing, cannibalization and recycling [2-4]. Also, these options are to be reclassified into three broad categories such as reuse, recycling, and remanufacturing. In reuse, the returned product can be used more than once in the same form

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after cleaning or reprocessing. On the other hand, recycling denotes material recovery without conserving any product structure. Finally, remanufacturing is an industrial process in which worn-out products are restored to like-new condition.

The design/redesign of the supply chain with return flows has become a challenge for many companies. This is an important area of research as it helps lowering costs, while improving coordination and customer service [5]. For instance, Nike, the shoe manufacturer encourages consumers to bring their used shoes to the store where they had purchased them. These shoes are then shipped back to Nike's plants and made in to basketball courts and running tracks. By donating the material to the basketball courts and donating funds for building and maintaining these courts, Nike has enhanced the value of its brand [1]. Furthermore, according to other advocators' opinions, effective reverse supply chain activities can enhance relationships with consumers and supply chain partners, can be a source of significant cost savings, and can even function as a profit center [6].

According to know the importance of reverse supply chain for saving cost and improvement of customer loyalty and futures sales we propose a framework and a mathematical model for costs in a multilayer multi-product in reverse supply chain system.

This paper is organized as follows. In the next section, we introduce some key literatures relevant to this study. In Section 3, a general framework and problem definition for reverse supply chain are proposed. Section 4 proposes the mathematical model of the reverse supply chain. In Section 5, numerical experiments are presented. Finally conclusions and further researches are addressed in the last section.

2 Related literature

For the last decade, increasing concerns over environmental degradation and increased opportunities for cost savings or revenues from returned products prompted some researchers to formulate more effective reverse logistics strategies. These researchers including Salema et al. [7] have proposed a MILP model to analyze the problem of closed loop supply chains. They consider multi-product returns with uncertain behavior but limit their consideration of demand for returned products to factories and not to secondary markets or spare markets. Thus a supplier network which may be required to remanufacture a new product to meet the market demand is not considered. Also, this model is not suitable for modular products.

Del Castillo and Cochran [8] presented a pair of linear programs and a simulation model to optimally configure the reverse logistics network involving the return of reusable containers in such a way that the number of reusable containers was maximized. However, they did not take into account transportation issues related to reverse logistics. Pati et al. [9] have formulated a mixed integer goal programming model for analyzing paper recycling network. The model assumes five echelons and studies the inter-relationship between cost reduction, product quality improvement through increased segregation at the source, and environmental benefits through waste paper recovery. The model also assists in determining the facility location, and route and flow of different varieties of recyclable wastes. Aras et al. [10] developed a non-linear model and tabu search solution approach for determining the locations of collection centers and the optimal purchase price of used products in a simple profit maximizing reverse logistics network.

Initiating product recovery network design efforts, Thierry [11] introduced a linear program to design product distribution and product recovery networks involving the collection of used copying machines. However, his model did not address the location issue of

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where the product recovery (resale of products after remanufacturing and refurbishment) process should be installed and at what capacity. Krikke [12] proposed a network graph and a mixed integer program to optimize the degree of disassembly and evaluate product recovery options in collecting used copying machines and redistributing them after refurbishment, while determining the location and capacity of remanufacturing, central stocking, and disposal facilities. Similarly, Krikke et al. [13] developed a mixed integer program to determine the locations of shredding and melting facilities for the recovery and disposal of used automobiles, while determining the amount of product flows in the reverse logistics network. Jayaraman et al. [14] presented a mixed integer program to determine the optimal number and locations of remanufacturing facilities for electronic equipment. Jayaraman et al. [15] extended their prior work to solve the two-level hierarchical location problem involving the reverse logistics operations of hazardous products. They also developed heuristic concentration procedures combined with heuristic expansion components to handle relatively large problems with up to 40 collection sites and 30 refurbishment sites. Despite their success in solving large-sized problems, their model and solution procedures are still confined to a single period problem and are not designed to deal with the possibility of making trade-offs between freight rate discounts and inventory cost savings resulting from consolidation of returned products. Lee and Dong [16] develop an MILP model for integrated logistics network design for end-of-lease computer products. They consider a simple network with a single production center and a given number of hybrid distribution-collection facilities to be opened which they solve using tabu search. However, all of researches are found for some cost in reverse logistics that contain and define some centers. Our study focuses on a general framework and state total cost in reverse supply chain.

3 Problem definition

The reverse supply chain under study is multi-layer, multi-product. In the designed (planned) model, the returned products after collecting and inspecting is divided into two groups of disassembling and not disassembling products. The products which can be taken parted to the parts will be sent to the disassembly centers and there, they will be converted to the parts. There they are divided into reusable and not reusable parts. In the recycling process according to the recycling centers demand the disassembled parts (which can recover again) right after disassembly centers will be sent to the recycling centers for the purpose of producing the secondary materials. Some of the products that don't need to be disassembled; according to their variety will be transmitted to the processing center right after collecting centers, then considering to the variety of product and the request of manufacturing centers or recycling centers, will be sent to them (or will be sent to those centers). In the remanufacturing process, according to the production center's demand, the parts which can be used again, after processing center will be sent to the remanufacturing center and after compounding with the other parts will be changed into new products and can return to the distribution chain. The configuration is shown in Fig. 1.

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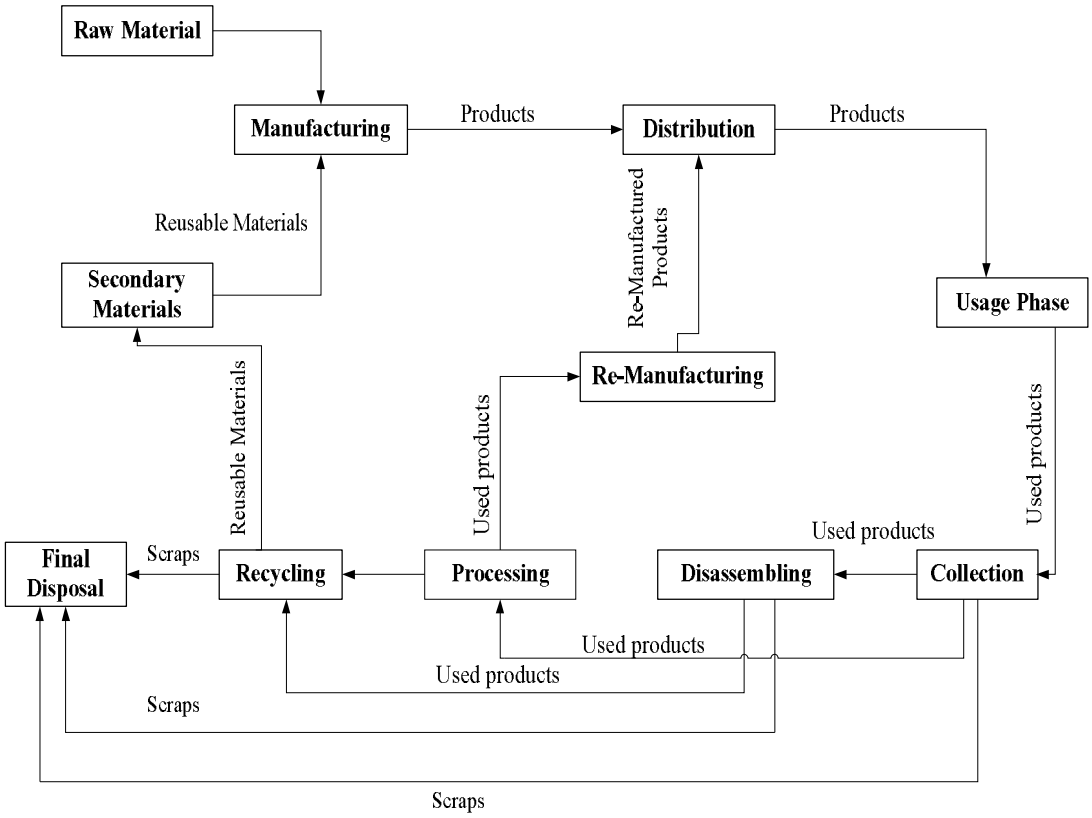


Fig. 1 Framework for reverse supply chain

3.1 Purpose

In this paper the reverse supply chain model has been considered for returned products with the purpose of minimizing the reverse supply chain costs.

3.2 Assumptions

- The quantity of return, disassembly, processing, manufacturing, recycling, material and distribution centers are determined.
- Some products will transport straightly from return centers to the processing centers.
- Some parts will transport straightly from disassembly centers to the recycling centers.

3.3 Indices, Parameters, and Decision variables

Indices:
i : index of returning centers
j : index of disassembly centers
k : index of processing center
f : index of manufacturing center
r : index of recycling center
w : index of material

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p : index of products
m : index of parts
l : index of distribution centers
c : index of clients

Parameters:
a_{ip} : the capacity of returning center i for product p
b_{jm} : The capacity of disassembly center j for parts m
u_{km} : The capacity of processing center k for part m
d_{rm} : The capacity of recycling center r for part m
h_{fm} : The capacity of manufacturing center f for parts m
E_{lm} : The capacity of distribution center l for part m
DM_{fm} : the manufacturing center's demand f for part m
$DRCP_{rp}$: the recycling center's demand r for product p
$DRCM_{rm}$: the recycling center's demand r for part m
DD_{lm} : the distribution center's demand l for part m
DC_{cm} : the client's demand c for part m
DMA_{wm} : the material center's demand w for part m
n_{mp} : The produced part's amount m from disassembling one product p.
$CSRD_{ijp}$: unit cost of transportation from returning center i to disassembly center j for product p
$CSRP_{ikp}$: unit cost of transportation from returning center i into the processing center k for product p
$CSDRC_{jrm}$: unit cost of transportation from disassembly center j into the recycling center r for part m
$CSPM_{kfm}$: unit cost of transportation from processing center k into the manufacturing center f for part m
$CSPRC_{krm}$: unit cost of transportation from processing center into the recycling center r for part m
$CSRCM_{rwm}$: unit cost of transportation from recycling center r into the material center w for part m
$CSPDC_{flm}$: unit cost of transportation from manufacturing center f into the distribution center l for part m
$CSDC_{lcm}$: unit cost of transportation from distribution center l into the clients c for part m
$FOCD_{jm}$: the fixed opening cost for disassembly center j for part m
$FOCP_{km}$: the fixed opening cost for processing centers k ,for part m
$FOCR_{ip}$: the fixed opening cost for returning centers i for product p
$FOCRC_{rm}$: the fixed opening cost for recycling centers r for part m
RMC_{fm} : unit cost of remanufacturing in manufacturing center f for part m
IC_{ip} : unit cost of maintaining in returning center i for product p
OCD_{jm} : unit cost of operations in disassembly center j for part m
OCP_{km} : unit cost of operations in processing center k part m
$OCRC_{rm}$: unit cost of operations in recycling center r part m
NRS_{min} : the minimum amount of returning center for opening and operations
NRS_{max} : the maximum amount of returning centers for operations and opening
NDS_{min} : the minimum amount of disassembly centers for opening and operations
NDS_{max} : the maximum quantity of disassembly centers for opening and operations
NPS_{min} : the minimum amount of processing centers for opening and operations

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NPS_{max} : the maximum amount of processing centers for opening and operations
$NRCS_{min}$: the minimum amount of recycling centers for opening and operations
$NRCS_{max}$: the maximum amount of recycling centers for opening and operations

Decision variables:
φ_{ijp} : amount shipped from returning center i to disassembly center j for product p
δ_{ikp} : amount shipped from returning center i into the processing center k for product p
O_{jrm} : amount shipped from disassembly center j into the recycling center r for part m
Q_{kfm} : amount shipped from processing center into the manufacturing center f for part m
S_{krm} : amount shipped from processing center k into the recycling center r for part m
ρ_{rwm} : amount shipped from recycling center r into the material center w for part m
T_{flm} : amount shipped from manufacturing center f into the distribution center l for part m
V_{lcm} : amount shipped from distribution center l into the clients c for part m
α_{jm} : if the disassembly center j is open for part m ,1or otherwise 0
β_{km} : if processing center k is open for part m 1 or otherwise 0
γ_{ip} : if the returning center j is open for product p, 1 or otherwise 0
λ_{rm} : if recycling center r is open for part m , 1 or otherwise 0
μ_{fm} : the part's flow amount m in manufacturing center f
X_{ip} **:** the product's flow amount p in returning center i
Y_{jm} : the part's flow amount m in disassembly j
θ_{km} : the part's flow amount m in processing center k
τ_{rm} : the part's flow amount m in recycling center r

4 Mathematical formulation

The formulation of the mathematical model is given below:

$$\begin{aligned} Min\ \ Z = & \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P} csrd_{ijp}\Phi_{ijp} + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{p=1}^{P} csrp_{ikp}\delta_{ikp} + \sum_{j=1}^{J}\sum_{r=1}^{R}\sum_{m=1}^{M} csdrc_{jrm}O_{jrm} + \sum_{k=1}^{K}\sum_{f=1}^{F}\sum_{m=1}^{M} csrm_{kfm}Q_{kfm} + \\ & \sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{m=1}^{M} csprc_{krm}S_{krm} + \sum_{r=1}^{R}\sum_{w=1}^{W}\sum_{m=1}^{M} csrcm_{rwm}\rho_{rwm} + \sum_{f=1}^{F}\sum_{l=1}^{L}\sum_{m=1}^{M} cspdc_{flm}T_{flm} + \sum_{l=1}^{L}\sum_{c=1}^{C}\sum_{m=1}^{M} csdc_{lcm}V_{lcm} + \\ & \sum_{j=1}^{J}\sum_{m=1}^{M} focd_{jm}\alpha_{jm} + \sum_{k=1}^{K}\sum_{m=1}^{M} focp_{km}\beta_{km} + \sum_{i=1}^{I}\sum_{p=1}^{P} focr_{ip}\gamma_{ip} + \sum_{r=1}^{R}\sum_{m=1}^{M} focrc_{rm}\lambda_{rm} + \sum_{f=1}^{F}\sum_{m=1}^{M} rmc_{fm}\mu_{fm} + \\ & \sum_{i=1}^{I}\sum_{p=1}^{P} ic_{ip}X_{ip} + \sum_{j=1}^{J}\sum_{m=1}^{M} ocd_{jm}Y_{jm} + \sum_{k=1}^{K}\sum_{m=1}^{M} ocp_{km}\theta_{km} + \sum_{r=1}^{R}\sum_{m=1}^{M} ocrc_{rm}\tau_{rm} \end{aligned} \quad (1)$$

s.t.

$$\sum_{j=1}^{J}\Phi_{ijp} \le a_{ip}\gamma_{ip} \quad \forall i,p \quad (2)$$

$$\sum_{k=1}^{K}\delta_{ikp} \le a_{ip}\gamma_{ip} \quad \forall i,p \quad (3)$$

$$X_{ip} \le a_{ip}\gamma_{ip} \quad \forall i,p \quad (4)$$

$$\sum_{r=1}^{R}O_{jrm} \le b_{jm}\alpha_{jm} \quad \forall j,m \quad (5)$$

$$Y_{jm} \le b_{jm}\alpha_{jm} \quad \forall j,m \quad (6)$$

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$$\sum_{f=1}^{F} Q_{kfm} \le u_{km}\beta_{km} \quad \forall k,m \tag{7}$$

$$\sum_{r=1}^{R} S_{krm} \le u_{km}\beta_{km} \quad \forall k,m \tag{8}$$

$$\theta_{km} \le u_{km}\beta_{km} \quad \forall k,m \tag{9}$$

$$\sum_{w=1}^{W} \rho_{rwm} \le d_{rm}\lambda_{rm} \quad \forall r,m \tag{10}$$

$$\sum_{l=1}^{L} T_{flm} \le h_{fm} \quad \forall f,m \tag{11}$$

$$\mu_{fm} \le h_{fm} \quad \forall f,m \tag{12}$$

$$\sum_{c=1}^{C} V_{lcm} \le e_{lm} \quad \forall l,m \tag{13}$$

$$\sum_{k=1}^{K} Q_{kfm} \ge DM_{fm} \quad \forall f,m \tag{14}$$

$$\mu_{fm} \ge DM_{fm} \quad \forall f,m \tag{15}$$

$$\sum_{f=1}^{F} T_{flm} \ge DD_{lm} \quad \forall l,m \tag{16}$$

$$\sum_{l=1}^{L} V_{lcm} \ge DC_{cm} \quad \forall c,m \tag{17}$$

$$\sum_{r=1}^{R} \rho_{rwm} \ge DMA_{wm} \quad \forall w,m \tag{18}$$

$$\sum_{j=1}^{J} O_{jrm} + \sum_{k=1}^{K} S_{krm} \ge DRCM_{rm} \quad \forall r,m \tag{19}$$

$$\tau_{rm} \ge DRCM_{rm} \quad \forall r,m \tag{20}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} \delta_{ikp} \ge \sum_{r=1}^{R} DRCP_{rp} \quad \forall p \tag{21}$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R} O_{jrm} \le n_{mp}\left(\sum_{i=1}^{I}\sum_{j=1}^{J} \Phi_{ijp}\right) \quad \forall m,p \tag{22}$$

$$NRS_{\min} \le \sum_{i=1}^{I} \gamma_{ip} \le NRS_{\max} \quad \forall p \tag{23}$$

$$NDS_{\min} \le \sum_{j=1}^{J} \alpha_{jm} \le NDS_{\max} \quad \forall m \tag{24}$$

$$NPS_{\min} \le \sum_{k=1}^{K} \beta_{km} \le NPS_{\max} \quad \forall m \tag{25}$$

$$NRCS_{\min} \le \sum_{r=1}^{R} \lambda_{rm} \le NRCS_{\max} \quad \forall m \tag{26}$$

$$\sum_{f=1}^{F} T_{flm} = \sum_{c=1}^{C} V_{lcm} \quad \forall l,m \tag{27}$$

$$\sum_{r=1}^{R} O_{jrm} \le Y_{jm} \quad \forall j,m \tag{28}$$

$$\sum_{j=1}^{J} \Phi_{ijp} + \sum_{k=1}^{K} \delta_{ikp} \le X_{ip} \quad \forall i,p \tag{29}$$

$$\sum_{f=1}^{F} Q_{kfm} + \sum_{r=1}^{R} S_{krm} \le \theta_{km} \quad \forall k,m \tag{30}$$

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$$\sum_{w=1}^{W} \rho_{rwm} \le \tau_{rm} \quad \forall r, m \tag{31}$$

$$\sum_{l=1}^{L} T_{flm} \le \mu_{fm} \quad \forall f, m \tag{32}$$

$$\Phi_{ijp}, \delta_{ikp}, O_{jrm}, Q_{kfm}, S_{krm}, \rho_{rwm}, T_{flm}, V_{lcm}, \mu_{fm}, X_{ip}, Y_{jm}, \theta_{km}, \tau_{rm} \ge 0 \quad \forall i, j, k, f, r, w, p, m, l, c \tag{33}$$

$$\alpha_{jm}, \beta_{km}, \gamma_{ip}, \lambda_{rm} = \{0,1\} \quad \forall i, j, k, p, m \tag{34}$$

Objective function:

We want to demonstrate a model in reverse supply chain in a way to minimize the chain costs. We should introduce a model which minimizes the transportation cost of products and parts between centers and at the same time minimizes the fixed opening cost of sites and operation's cost on parts and supply maintenance costs and remanufacturing costs. By attention to the definition of Indices, parameters and Decision variables; the objective function will be defined , which consists of : minimizing the costs of transportation of products and parts, the fixed opening cost of centers and operations costs on parts and the supply maintenance costs, remanufacturing costs in reverse supply chain.(1)

Constraints:

(2,3) These constraints are decelerating that the amount of shipping products from any returning center (if it is opened)into the disassembly, processing centers for each product should be equal or smaller than the capacity of that returning center.

(4) This constraint is stating that the amount of products which will be collected in the returning center should be equal or smaller than the capacity of that returning center.

(5) This constraint is stating that the amount of sent parts from any disassembly centers into recycling centers should be equal or smaller than the capacity of the same disassembly center for each part.

(6) This constraint is stating that the amount of a part which is in the disassembly center should be equal or smaller than the capacity of the same disassembly center.

(7)and(8) These constraints are stating that the amount of shipping parts from any processing centers (if it is opened)into the manufacturing centers and recycling centers should be equal or smaller than the capacity of the same processing centers for each parts.

(9) This constraint is stating that the amount of a part which is in the processing center should be equal or smaller than the capacity of the same processing center.

(10) This constraint is stating that the amount of the parts which shipping from any recycling center (if it is opened)into the material centers should be equal or smaller than the capacity of the same recycling for each part.

(11) This constraint states that the amount of sent parts from any manufacturing center into the distribution centers should be equal or smaller than the capacity of the same manufacturing center for each part.

(12) This constraint states that the amount of part in each manufacturing center should be equal or smaller than the capacity of the same manufacturing center.

(13) This constraint states that the amount of sent parts from any distribution center to the client should be equal or smaller than the capacity of the same distribution center for clients.

(14)and(15) states the demand amount of manufacturing center for parts

(16) states the part demand amount of distribution centers.

(17) indicates the client's part demand amount.

(18) states the part demand amount of material center.

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(19)and(20) states the part demand amount of recycling centers.
(21) states that the recycling center's demand, is for products which is transported from the returning center into the processing center .
(22) This constraint is related to the balance of parts flow from the disassembly of products.
(23),(24),(25),(26) these constraints are stating that the min and max index amount of returning , disassembly, processing and recycling centers .
(27) This constraint states that the amount of sent parts from manufacturing centers to the distribution center is equal to the sent parts from distribution centers in to the client.
(28) This constraint states that the amount of sent parts from each disassembly center into the recycling center should be equal or smaller than the parts amount in that disassembly center.
(29) These constraint states that the amount of sent products from each returning center into the disassembly, processing centers , should be equal or smaller than the product's amount in that returning center.
(30) These constraint state that the amount of sent parts from each of the processing centers into the manufacturing and recycling centers should be equal or smaller than the flow amount of parts in that processing center.
(31) This constraint states that the sent parts amount from any recycling center into the material centers should be equal or smaller than the parts amount in that recycling center.
(32) This constraint states that the sent parts amount from any manufacturing center into the distribution centers should be equal or smaller than the parts flow amount in that manufacturing center.
(33) and (34) enforce the binary and non- negativity restrictions on the corresponding decision variables.

5 Numerical experiment

We solved the presented mathematic model by using Lingo 9, which is an operation research software. In this multi-layers and multi-products model, we are attempting to minimize the costs of fixed opening facilities, transportation and shipping of products and parts between centers and also the operations, supply maintenance and remanufacturing costs, and also the product amount and sending parts into the centers and the amount of it would be calculated. To analyzing the suggested model we create the numerical example in small size and then solve the created example by lingo software.

In small size we consider the index quantities as variables between 3 to 5 to solve the problem, so we replace the inputs of problem in the model and by using the lingo we will solve the problem, and finally the model solving outputs and the objective function amount and the implementation time of it would be demonstrated.

By attention to the inputs of the model and solving it, the outputs of model and objective function amount and the implementation time has been obtained which are as follow;

The obtained objective function is 25627.6 which obtained in zero time. All the variables which were not zero 0 quantities are shown in table (1);

After solving the model we will find out that the decision variable $\beta(1,1)$ gained 1quantity. This means that the processing center 1 should be opened for part 1. The decision variable $\gamma(2,4)$ obtained 1, means that the returning center 2 would be opened for part 4. Generally when the decision variables α_{jm}, β_{km}, γ_{ip}, λ_{rm} gained 1, it indicates that the considered center to that decision variable will be opened for that part or product.

The decision variable $\delta(2,1,2)$ is considered 34. This means that the amount of part 2 from

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returning center 2 into the processing center 1 is 34.the decision variable $\theta(2,3)$ got 63, it means that the amount of part 3 in processing center 2 is 63. $V(1,4,1)=20$ means that the amount of part 1 from distribution center 1 into the client 4 is 20.

Table 1 Numerical results using LINGO 9 Software

$\varphi(2,1,4)$	0.35	$\rho(3,3,2)$	14	$\theta(2,2)$	16
$\varphi(2,3,2)$	0.21	T(1,1,3)	6	$\theta(2,3)$	59
$\varphi(3,3,1)$	0.24	T(1,2,1)	8	$\theta(3,1)$	8
$\varphi(3,3,3)$	0.32	T(1,2,3)	13	$\theta(4,2)$	20
$\delta(2,1,2)$	34	T(1,3,2)	3	$\theta(4,3)$	11
$\delta(2,4,4)$	28	T(2,1,2)	7	$\gamma(2,1)$	1
$\delta(3,1,1)$	41	T(2,2,3)	17	$\gamma(2,2)$	1
$\delta(3,4,3)$	8	T(2,3,1)	24	$\gamma(2,3)$	1
O(1,1,3)	12	T(2,3,3)	16	$\gamma(2,4)$	1
O(1,3,2)	18	T(3,2,1)	8	$\gamma(3,1)$	1
O(1,3,3)	4	T(3,2,2)	8	$\gamma(3,2)$	1
O(2,3,1)	18	T(4,1,1)	13	$\gamma(3,3)$	1
Q(1,1,1)	9	T(4,2,1)	3	$\gamma(3,4)$	1
Q(1,1,2)	17	T(4,2,2)	5	X(2,2)	34.21
Q(1,2,1)	18	T(5,1,1)	8	X(2,4)	28.35
Q(1,2,2)	16	T(5,1,2)	16	X(3,1)	41.24
Q(1,3,2)	8	T(5,3,3)	17	X(3,3)	8.32
Q(1,4,1)	16	V(1,1,2)	6	$\lambda(1,1)$	1
Q(1,4,2)	5	V(1,1,3)	6	$\lambda(1,2)$	1
Q(1,5,1)	8	V(1,2,2)	17	$\lambda(1,3)$	1
Q(2,1,3)	19	V(1,3,1)	1	$\lambda(2,1)$	1
Q(2,3,3)	14	V(1,4,1)	20	$\lambda(2,2)$	1
Q(2,4,3)	9	V(2,1,2)	4	$\lambda(2,3)$	1
Q(2,5,2)	16	V(2,2,3)	16	$\lambda(3,1)$	1
Q(2,5,3)	17	V(2,3,1)	19	$\lambda(3,2)$	1
Q(3,3,1)	8	V(2,4,2)	9	$\tau(1,1)$	32
Q(4,2,3)	7	V(2,4,3)	14	$\tau(1,2)$	20
S(1,1,1)	16	V(3,1,1)	20	$\tau(1,3)$	12
S(1,2,1)	4	V(3,1,3)	13	$\tau(2,1)$	17
S(1,2,2)	11	V(3,2,1)	4	$\tau(2,2)$	11
S(4,1,2)	20	V(3,3,2)	3	$\tau(2,3)$	15
S(4,2,3)	4	V(3,3,3)	20	$\tau(3,1)$	18
$\rho(1,1,1)$	1	$\alpha(1,2)$	1	$\tau(3,2)$	25
$\rho(1,1,2)$	12	$\alpha(1,3)$	1	$\tau(3,3)$	4
$\rho(1,2,1)$	17	$\alpha(2,1)$	1	$\mu(1,1)$	9
$\rho(1,2,3)$	6	$\alpha(2,2)$	1	$\mu(1,2)$	17
$\rho(1,4,1)$	14	$\alpha(3,1)$	1	$\mu(1,3)$	19

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ρ(1,4,3)	2	α(3,3)	1	μ(2,1)	24
ρ(1,5,2)	8	Y(1,2)	18	μ(2,2)	16
ρ(1,5,3)	4	Y(1,3)	16	μ(2,3)	33
ρ(2,1,3)	1	Y(2,1)	18	μ(3,1)	8
ρ(2,3,1)	1	β(1,1)	1	μ(3,2)	8
ρ(2,3,3)	1	β(1,2)	1	μ(3,3)	14
ρ(2,4,2)	4	β(2,2)	1	μ(4,1)	16
ρ(2,5,1)	16	β(2,3)	1	μ(4,2)	5
ρ(2,5,2)	7	β(3,1)	1	μ(4,3)	9
ρ(2,5,3)	13	β(4,2)	1	μ(5,1)	8
ρ(3,1,2)	3	β(4,3)	1	μ(5,2)	16
ρ(3,2,2)	8	θ(1,1)	71	μ(5,3)	17
ρ(3,3,1)	18	θ(1,2)	57		

6 Conclusions

In this paper, a reverse supply chain was considered minimizing the total cost of transport, remanufacture and maintenance. The presented model was an integer linear programming model for multi-layer, multi-product reverse supply chain that minimizes the products and parts transportation costs among centers and also sites launch, operation parts, maintenance and remanufacturing costs at the same time. We solved the proposed model using Lingo 9 software.

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