Mathematical Modeling for Optimal Facility Location and Product Flow in A Multi-layer Multi-product Reverse Supply Chain

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Abstract: With the increased environmental concerns and stringent environmental laws, reverse logistics has received growing attention throughout this decade. This paper presents a mathematical programming model which minimizes the total cost of reverse supply chain including transportation costs among centers and also sites launch, operation parts, maintenance and remanufacturing costs. The proposed model considers the design of a multi-layer, multi-product reverse supply chain that consists of returning, disassembly, processing, recycling, remanufacturing, materials and distribution centers. Reverse flow starts with the collection of the returned products. These products are first received at returning sites and then transported to other sites. Based on the proposed model, the optimal facility locations and the products and parts flows in the reverse supply chain can be determined. Finally, a numerical example is illustrated to achieve a better vision into the proposed model.

Keywords: Reverse supply chain, Mathematical modeling, Optimal flow, Facility location

1 INTRODUCTION

In recent years, concern for the environment has increased for a number of reasons. Firstly, as a result of the important negative environmental impacts that company products and processes are producing [1]. Secondly, due to the pressure that society is exerting on its institutions to address environmental issues [2], which translates as new legal demands (for example, European Union laws require manufacturers to collect and reuse many types of products). Thirdly, managers appreciate the benefits to their company image of adopting environmentally concerned programs [3]. Lastly, consumers have changed their preferences, which are transferred the entire value chain [4], modifying the responsibilities of suppliers and manufacturers with regards to the products they place on the market [5].

Generally, companies focus on setting up a reverse supply chain either because of environmental regulations or to reduce their operating costs by reusing products or components. For example, beginning in 2003 European Union legislation has required tire manufacturers operating in Europe to arrange for the recycling of one used tire for every new tire they sell [6]. Furthermore, Xerox's green remanufactuing program, which collects used copiers directly from users as new ones are installed, saves the company 40–65% in manufacturing cost through the reuse of parts and materials [7].

2 PROBLEM DEFINITION

Reverse logistics is the collection and transportation of used products and packages [8]. Various researchers classified the reverse logistic process differently. Fleischmann et al. [9] categorized the recovery process into collection, inspection/separation, re-processing, disposal and re-distribution. Thierry et al. [10] divided recovery into repair, refurbish, remanufacture, cannibalize, and recycle. Liu et al. [11] and He et al. [12] defined recovery process as a combination of re-

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use, service, re-manufacture, recycle, and disposal. Reusable parts can be removed from the product, returned to a manufacturer where they can be reconditioned and assembled into new products [13]. Recycling (with or without disassembly) includes the treatment, recovery, and reprocessing of materials contained in the used products or components in order to replace the virgin materials in the production of new goods [12]. Re-manufacturing is the process of removing specific parts of the waste product for further reuse in new products. Disposal is the processes of incineration or landfill [12].

According to this definition of reverse supply chain we propose a framework and a mathematical model for costs in a multi-layer, multi-product in reverse supply chain system.

The rest of the paper is organized as follows. Section 2 presents a brief review of the literature on reverse supply chain. A general framework and problem definition for reverse supply chain are described in Section 3. The proposed the mathematical model of the reverse supply chain is given in Section 4. Numerical experiments are provided in Section 5. Finally conclusions and further researches are addressed in the last section.

3 RELATED LITERATURE

Sheu et al. [14] formulated a linear multi objective programming model to optimize the operations of both integrated logistics and corresponding used-product reverse logistics in a given green-supply chain. Factors such as the used-product return ratio and corresponding subsidies from governmental organization for reverse logistics were considered in the model formulation. The authors also proposed a real world case study for a Taiwan based notebook computer manufacturer. Jayaraman et al. [15] presented a mixed-integer linear programming model to determine optimal quantities of remanufactured products and used parts in a reverse supply chain network. Fleischmann et al. [16] extended a forward logistics model to a reverse logistics system and discussed the differences. They utilized mixed-integer linear programming model. Kannan et al. [17] proposed a model using genetic algorithm and particle swarm techniques. They applied the model by considering two cases including a tyre manufacturer and a plastic goods manufacturer. Shi et al. [18] proposed a mathematical model to maximize the profit of a remanufacturing system by developing a solution approach based on Lagrangian relaxation method.

Wang and Hsu [19] proposed an interval programming model where the uncertainty has been expressed by fuzzy numbers. Schultmann et al. [20] developed a hybrid method to establish a closed-loop supply chain for spent batteries. The model included a two stage (collection point-sorting – recycling or disposal) facility location optimization problem. The authors found the optimal sorting centers to open to serve the recycling facilities through a mixed integer linear programming model which minimizes the total cost, and implemented the model in GAMS (General Algebraic Modeling System) and solved it using a branch-and-bound algorithm. As a hybrid method, it also approached to a simulation under different scenarios for a steel making process. Listes [21] presented a generic stochastic model for the design of networks comprising both supply and return channels, organized in a closed loop system. The author described a decomposition approach to the model, based on the branch-and-cut procedure known as the integer L-shaped method. Gupta and Evans [22] proposed a non-preemptive goal programming approach to model a closed-loop supply chain network.

Kannan et al. [23] developed a mathematical model for a case of battery recycling. However, they did not consider uncertainty of parameters. Amin and Zhang [24] designed a network based on product life cycle. They utilized mixed-integer linear programming to configure the network. Du and Evans [25] developed a bi-objective model for a reverse logistics network by considering minimization of the overall costs, and the total tardiness of cycle time.

Pishvaee et al. [26] considered minimization of the total costs, and maximization of the responsiveness of a logistics network. Min et al. [27] proposed a mixed integer non-linear programming model to minimize the total reverse logistics costs for the reverse logistics problem involving both spatial and temporal consolidation of returned products. Fuente et al. [28] proposed an integrated model for supply chain management (IMSCM) in which the operation of the reverse chain had been built based on the existing processes of the forward chain. Finally the proposed model had been validated in a company from the metal-mechanic sector. However, all of researches are found for some cost in reverse logistics. Our study focuses on a general framework and state total cost in reverse supply chain.

This paper propose multi layers, multi products reverse supply chain problem which consist of; returning center, disassembly center, processing center, manufacturing center, recycling center, material center and distribution center which consider the minimizing of total costs in reverse supply chain for returned products.

The reverse supply chain under study is multi-layer, multi-product. In the designed (planned) model, the returned products after collecting and inspecting divides 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 convert to the parts. There they divide into reusable and not reusable parts. The not reuseable parts will rebut safely and the reuseable parts will be sent to the processing center. Some of the products that don't need to be disassembling; 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.

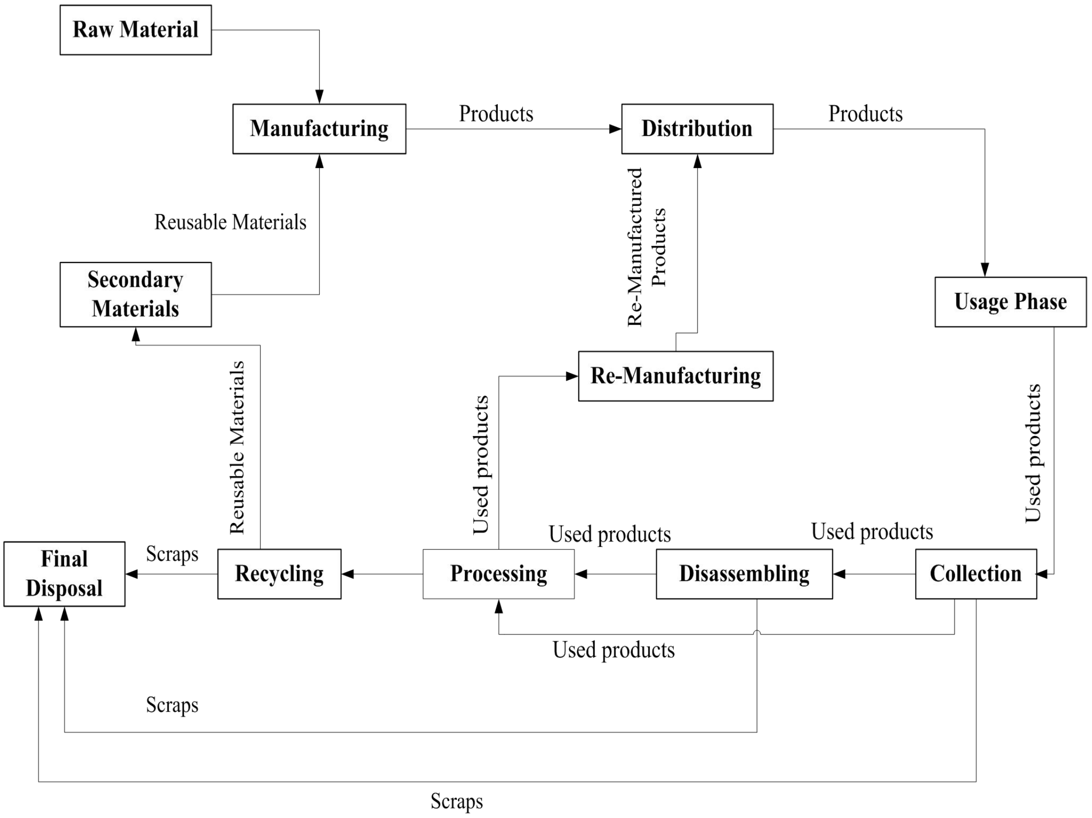

Fig. 1. Framework for reverse supply chain

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.

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
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 production 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 disassembly 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

$CSDP_{jkm}$: unit cost of transportation from disassembly center j into processing center k 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 k 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

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 disassembling center j for product p

δ_{ikp} : amount shipped from returning center i into the processing center k for product p

G_{jkm} : amount shipped from disassembly center j into the processing center k for part m

Q_{kfm} : amount shipped from processing center k 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

3.4 Mathematical formulation

The formulation of the mathematical model is given below:

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

$$\text{s.t.} \sum_{j=1}^{J} \Phi_{ijp} \le a_{ip}\gamma_{ip} \quad \forall i,p \tag{2}$$

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

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

$$\sum_{k=1}^{K} G_{jkm} \le b_{jm}\alpha_{jm} \quad \forall j,m \tag{5}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\sum_{j=1}^{J}\sum_{k=1}^{K} G_{jkm} \ge \sum_{f=1}^{F} DM_{fm} \quad \forall m \tag{22}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} G_{jkm} \le n_{mp}\left(\sum_{i=1}^{I}\sum_{j=1}^{J} \Phi_{ijp}\right) \quad \forall m,p \tag{23}$$

$$NRS_{\min} \le \sum_{i=1}^{I} \gamma_{ip} \le NRS_{\max} \quad \forall p \tag{24}$$

$$NDS_{\min} \le \sum_{j=1}^{J} \alpha_{jm} \le NDS_{\max} \quad \forall m \tag{25}$$

$$NPS_{\min} \le \sum_{k=1}^{K} \beta_{km} \le NPS_{\max} \quad \forall m \tag{26}$$

$$NRCS_{\min} \le \sum_{r=1}^{R} \lambda_{rm} \le NRCS_{\max} \quad \forall m \tag{27}$$

$$\sum_{f=1}^{F} T_{flm} = \sum_{c=1}^{C} V_{lcm} \quad \forall l,m \tag{28}$$

$$\sum_{k=1}^{K} G_{jkm} \le Y_{jm} \quad \forall j,m \tag{29}$$

$$\sum_{j=1}^{J} \Phi_{ijp} + \sum_{k=1}^{K} \delta_{ikp} \le X_{ip} \quad \forall i,p \tag{30}$$

$$\sum_{f=1}^{F} Q_{kfm} + \sum_{r=1}^{R} S_{krm} \le \theta_{km} \quad \forall k,m \tag{31}$$

$$\sum_{w=1}^{W} \rho_{rwm} \le \tau_{rm} \quad \forall r,m \tag{32}$$

$$\sum_{l=1}^{L} T_{flm} \le \mu_{fm} \quad \forall f,m \tag{33}$$

$$\begin{gathered}\Phi_{ijp}, \delta_{ikp}, G_{jkm}, Q_{kfm}, S_{krm}, \rho_{rwm}, T_{flm},\\ V_{lcm}, \mu_{fm}, X_{ip}, Y_{jm},\\ \theta_{km}, \tau_{rm} \ \ge\ 0\\ \forall i, j, k, f, r, w, p, m, l, c\end{gathered} \tag{34}$$

$$\alpha_{jm}, \beta_{km}, \gamma_{ip}, \lambda_{rm} = \{0,1\} \quad \forall i,j,k,p,m \tag{35}$$

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 shipping parts from any disassembly center into the processing 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.

(19) and (20) states the part demand amount of recycling centers.

(21) and (22) states that the manufacturing and recycling center's demand, is for products and parts which are transported from the returning and disassembly centers into the processing center .

(23) This constraint is related to the balance of parts flow from the disassembly of products.

(24), (25), (26), (27) these constraints are stating that the min and max index amount of returning, disassembling, processing and recycling centers.

(28) 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.

(29) This constraint states that the amount of sent parts from each disassembly center into the processing center should be equal or smaller than the parts amount in that disassembly center.

(30) this 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.

(31) 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.

(32) 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.

(33) 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.

(34) and (35) enforce the binary and non-negativity restrictions on the corresponding decision variables.

3.5 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 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 3to5 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 demonstrate.

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 30072.2 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 β (1,3) gained 1quantity. This means that the processing center 1 should be opened for part3. The decision variable γ (3,2) obtained 1, means that the returning center 3 would be opened for part 2. 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 Q(1,2,1) is considered 17. This means that the amount of part 1 from processing center 1 into the manufacturing center 2 is 17.the decision variable θ(4,3) got 11 ,it means that the amount of part 3 in processing center 4 is 11. S(2,3,2) = 18 means that the amount of part 2 from processing center 2 into the recycling center 3 is 18.

Table (1): Numerical results using LINGO 9 Software

φ(2,1,4)	1.2	ρ(1,2,3)	6	V(2,4,2)	9	γ(3,3)	1
φ(2,3,2)	0.9	ρ(1,4,1)	14	V(2,4,3)	14	γ(3,4)	1
φ(3,3,1)	0.9	ρ(1,4,3)	2	V(3,1,1)	20	X(2,2)	34.9
φ(3,3,3)	1.1	ρ(1,5,2)	8	V(3,1,3)	13	X(2,4)	29.2
δ(2,1,2)	34	ρ(1,5,3)	4	V(3,2,1)	4	X(3,1)	41.9
δ(2,4,4)	28	ρ(2,1,3)	1	V(3,3,2)	3	X(3,3)	9.09
δ(3,1,1)	41	ρ(2,3,1)	1	V(3,3,3)	20	λ(1,1)	1
δ(3,4,3)	8	ρ(2,3,3)	1	α(1,2)	1	λ(1,2)	1
G(1,3,2)	62	ρ(2,4,2)	4	α(1,3)	1	λ(1,3)	1
G(1,4,3)	62	ρ(2,5,1)	16	α(2,1)	1	λ(2,1)	1
G(2,1,3)	4	ρ(2,5,2)	7	α(2,2)	1	λ(2,2)	1
G(3,2,1)	59	ρ(2,5,3)	13	α(2,3)	1	λ(2,3)	1
Q(1,1,1)	9	ρ(3,1,2)	3	α(3,1)	1	λ(3,1)	1
Q(1,1,2)	17	ρ(3,2,2)	8	Y(1,2)	62	λ(3,2)	1
Q(1,2,1)	17	ρ(3,3,1)	18	Y(1,3)	62	τ(1,1)	32
Q(1,2,2)	16	ρ(3,3,2)	14	Y(2,3)	4	τ(1,2)	20
Q(1,3,2)	8	T(1,1,3)	6	Y(3,1)	59	τ(1,3)	12
Q(1,4,1)	16	T(1,2,1)	8	β(1,1)	1	τ(2,1)	17
Q(1,4,2)	5	T(1,2,3)	13	β(1,2)	1	τ(2,2)	11
Q(1,5,1)	8	T(1,3,1)	1	β(1,3)	1	τ(2,3)	15
Q(1,5,3)	8	T(1,3,2)	3	β(2,1)	1	τ(3,1)	18
Q(2,1,3)	19	T(2,1,2)	7	β(2,2)	1	τ(3,2)	25
Q(2,2,1)	1	T(2,2,3)	17	β(2,3)	1	τ(3,3)	4
Q(2,3,3)	14	T(2,3,1)	23	β(3,1)	1	μ(1,1)	9
Q(2,4,3)	9	T(2,3,3)	16	β(4,2)	1	μ(1,2)	17
Q(2,5,2)	16	T(3,2,1)	8	β(4,3)	1	μ(1,3)	19
Q(2,5,3)	9	T(3,2,2)	8	θ(1,1)	72	μ(2,1)	23
Q(3,3,1)	8	T(4,1,1)	13	θ(1,2)	57	μ(2,2)	16
Q(4,2,3)	7	T(4,2,1)	3	θ(1,3)	12	μ(2,3)	33
S(1,2,1)	4	T(4,2,2)	5	θ(2,1)	17	μ(3,1)	8
S(1,2,2)	11	T(5,1,1)	8	θ(2,2)	34	μ(3,2)	8
S(1,3,1)	18	T(5,1,2)	16	θ(2,3)	63	μ(3,3)	14
S(1,3,3)	4	T(5,3,3)	17	θ(3,1)	8	μ(4,1)	16
S(2,1,1)	16	V(1,1,2)	6	θ(4,2)	20	μ(4,2)	5
S(2,1,3)	12	V(1,1,3)	6	θ(4,3)	11	μ(4,3)	9
S(2,3,2)	18	V(1,2,2)	17	γ(2,1)	1	μ(5,1)	8
S(4,2,3)	4	V(1,3,1)	1	γ(2,2)	1	μ(5,2)	16
S(4,1,2)	20	V(1,4,1)	20	γ(2,3)	1	μ(5,3)	17
ρ(1,1,1)	1	V(2,1,2)	4	γ(2,4)	1		
ρ(1,1,2)	12	V(2,2,3)	16	γ(3,1)	1		
ρ(1,2,1)	17	V(2,3,1)	19	γ(3,2)	1		

4 CONCLUSIONS

In this paper, a reverse supply chain was considered minimizing the total cost of transport, inspection, 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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