Single product multi period network design for reverse logistics and remanufacturing using new and old components

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Abstract. Reverse logistics has received considerable attention due to potentials of value recovery from the used products. Reverse Logistics network contains inputs, processes, and outputs. Inputs refer to used products and recycled materials. Used parts or new parts go through Reverse Logistics processes. Outcomes are remanufactured products, recycled materials and spare parts. In this paper, a mathematical model for the design of a RL network for multi period planning horizon is proposed. It is assumed that returned quantity of a product is collected at collection centers before they are sent to reprocessing centers for inspection and dismantling. Dismantled components are either sent for remanufacturing or to the secondary market as spare parts. Recycling and disposal of these components are also considered in the model. For future modifications in the network structure, we consider multi-period setting. We propose a single product formulation and use a reverse bill of materials. The use of the model is shown through its application in a numerical illustration.

Keywords: Reverse Logistics, Remanufactured Products, Recycle Materials, Reverse Bill Of Material.

1 Introduction

Logistic network design has an important and planned area in an efficient and effective supply chain management. Implementation of government legislation, environmental concern, social responsibility and customer awareness, has forced companies not only to supply environmentally friendly products but also to be responsible for the returned products. The rise of green concerns makes reverse logistics (RL) a time demanding and relevant area of interest. The Original equipment manufacturers (OEM's) are introducing new products in an effort to sustain/increase their market share; hence they are forced to take back their used, end of- lease or end-of-life products through a network for reuse, remanufacture, recycle and disposed of. Hence OEMs have turned to a better design of their products for maximum reuse and recycling so that maximum value can be achieved from their used products. A reverse logistics system comprises a series of activities such as collection, cleaning, disassembly, test and sorting, storage, transport, and recovery operations like reuse, repair, refurbishing, remanufacturing, cannibalization and recycling.

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The focus on RL is on waste management, material recovery, parts recovery or product recovery and the cost of recovered products can be reduced by optimal locations and allocations of facilities in RL. It prevents pollution by reducing the environmental burden of End-of-Life (EOL) at its source. Hence, an increasing number of companies now take into account reverse flows, going backwards from customers to recovery centers, within their logistics systems. Remanufacturing is recognized as a main option of recovery in terms of its feasibility and benefits.

2 Literature review

The fundamental studies on reverse logistics network design are driven by an application-oriented approach. Researchers have calculated that for recycling of the returned products, logistics costs account for a large share of the total costs [1], [2]. Transportation of used products is the most challenging issue in RL [3], [4] as smaller return quantities and variability in product types increase the transportation costs [5], [6]. [7] Emphasize on the need for collection centers in a reverse production system to help in maximizing collection of returned products. [8] developed truck sizing models for collection of wastes and transporting them to recovery centers. [9] Review on various quantitative models for RL networks. The location of collection points in a RL system has been examined by [10]. [11] proposed a MILP model by considering the reverse flow of goods.[12] proposed a product-recovery strategy depending on who collects the used products namely the manufacturer; the retailer; or a designated third party. [13] presented a multi-objective and multi- period MILP model for RL network design for modularized products. The authors have not considered the use of new components in remanufactured products.

Majority of the papers focus on recycling-only networks, such as [14] on battery recycling, [15] on tire recycling and [16] on paper recycling. Notable exceptions with a remanufacturing focus are [17] on copiers. [18] proposed a multi-period MILP model for carpet recycling. Their model analyses a set of alternative scenarios identified by the decision maker and provides a near optimal solution for network design. [19] proposed a MILP model to determine the optimal collection and recycling system for end-of-life computers and home appliances. [20] developed a model for the treatment of electrical and electronic wastes in Germany. [21] studied the implications of modular product architecture on RL strategies. Although the models proposed above are realistic representations of the network design problem regarding the specific application, but cannot be generalize to other industries. So, a more solid modeling framework for reverse logistics network design is given by [22] and describe that transportation and other logistics costs are not important factors in designing the RL network rather cost of reprocessing, remanufacturing and the cost of new components are deriving factors in designing of RL network.

Proposed model use a reverse bill of materials (BOM) to fit in component commonality in the product to handle return product for reuse. By using reverse BOM, the model also addresses the possibility of sending certain components to recycling/disposal and the possibility of purchasing new components for remanufacturing. Our modeling framework is applicable when the OEM has fairly reliable estimates of the amount of returns to be collected during the planning horizon as well as the demand at the secondary market for remanufactured products. To consider the

possibility of making future adjustments in the network configuration we present a multi-period model of the reverse network design problem.
The remainder of the paper is structured as follows. In Section 3 new model is proposed for multi-period reverse logistics network design. We also state the underlying assumptions and highlight the flexibility of our model in representing a wide variety of possible applications. In section 4, used methodology of differential evolution is described. In Section 5, we present a numerical implementation in order to highlight the features of the proposed model. The paper ends with our concluding remarks.

3 Model Description

Model presented here focused on modular product structure of single product in a RL network and on many features of practical relevance namely, a multi-period setting, reverse BOM, minimum throughput at the facilities, variable operational costs, and finite demands in the secondary market. In multi-period setting all network design decisions are taken over a planning horizon which implemented in the beginning or end of periods. Model considers that used products are collected at collection centers (CC) and send to reprocessing centers (RPC) for inspection and dismantling then inspected components are shipped to spare market, remanufacturing plant (RMP), recycling center (RC) or disposal site (DS) accordingly.

Model considers modular product structure with specifying disposal and recycling fractions. RL network discussed here supplies quality used components for remanufacturing and to the spare markets too. Mismatch of components for remanufacturing is assumed to be tackled by purchasing through pre-qualified suppliers. Larger price and quality differentials between the new and remanufactured product create demand for the remanufactured product. However this factor is not considered explicitly in the model. It is assumed that the spare parts, if any, can fetch a higher unit value compared to the remanufactured products. Also, if the numbers of components are in excess of demand, they are stored in the remanufacturing point till next period. Design of such a network is strategic as it involves a decision on the number of facilities, their locations and allocation of corresponding flow of used products and components at an optimal cost for a given market demand in the network flows. Demands for remanufactured products, spare markets are assumed to be deterministic. Network used for the analysis involves eight echelons: CC, RPC, RMP, RC, DS, spare parts markets, secondary markets (for remanufactured products) and preselected new component suppliers. Assumptions are as follows:

1 An infinite source of used product and used products are collected at prespecify collection centers. Goods collected in each CC transported to the reprocessing centers as soon as possible so that they do not incur any holding costs.
2 Dismantling operations are carried out in the RPC, where the components are disassembled, leaned, tested and sorted for reuse, remanufacture, spare and recycle. As a preference, spare market demands are met due to high value that it fetches from selling spare parts.
3 All the returned products are not suitable for remanufacturing. Therefore some new components may be required for remanufacturing. The final assembly of the product with the used and new components, if any is done inside the RMP.

RMP has inventory carrying cost for used components while it operates on Just-In-Time delivery of new components.

4 CC's, RPC's and RMP's are considered to have a monthly fixed cost. Transport cost is calculated with respect to the distance and overhead costs assuming full truck loads. Cost of new components ordered from pre-selected suppliers includes transportation cost also.

5 Shortages at secondary market are assumed to occur with no loss.

6 If the numbers of components are in excess of demand, then they are either recycled or stored in the RPC till further demand is received.

Notations:

Sets

CC set of collection centers indexed by 'cc'

J set of reprocessing centers (RPC) indexed by 'j'

S set of spare markets indexed by 's'

U set of remanufacturing plants (RMP) indexed by 'u'

X set of recycling plants (RP) indexed by 'x'

V set of disposal centers (DC) indexed by 'v'

Z set of new suppliers indexed by 'z'

H set of secondary markets (SM) indexed by 'h'

C set of components indexed by 'c'

T set of time periods indexed by 't'

Parameters

α No of components in one unit of product

ρ Recycling fraction

σ Disposal fraction

Q_{cc}^{t} Quantity of used product returned at collection center cc in period $t \in T$

D_{sc}^{t} Demand of component $c \in C$ in spare market $s \in S$ in period $t \in T$

D_{h}^{t} Demand of secondary market $h \in H$ in period $t \in T$

cap_j In bound capacity of RPC $j \in J$

$rcap_j$ Components reprocessing capacity of RPC $j \in J$

$pcap_u$ Production capacity of RMP $u \in U$

$icap_u$ Inventory holding capacity of RMP $u \in U$

$reccap_x$ Recycling capacity of RC $x \in X$

$discap_v$ Capacity of disposal center $v \in V$

$MTCC_{cc}$ Minimum throughput required for collection center $cc \in CC$

f_i^t Set-up cost of facility $i \in CC \cup J \cup U$ in the beginning of period $t \in T$

cdm_j^t Per unit product processing cost in RPC $j \in J$ in period $t \in T$

cr_{jc}^t Per unit component $c \in C$ reprocessing cost in RPC $j \in J$ in $t \in T$

cdp_{vc}^t Unit disposal cost for $c \in C$ in $v \in V$ in period $t \in T$

$casm_u^t$ Assembly cost /product for RMP plant $u \in U$ in period $t \in T$

c_{zuc}^t Unit cost of component c from supplier $z \in Z$ to RMP $u \in U$ in period t

IC_{uc}^t Unit inventory holding cost for $c \in C$ in RMP $u \in U$ in period $t \in T$

Tp_{ccj}^t Unit transportation cost of product from $cc \in CC$ to RPC $j \in J$ in $t \in T$

TS_{js}^t Unit transportation cost of $c \in C$ from RPC $j \in J$ to $s \in S$ in $t \in T$

T_{ju}^t Unit transportation cost of $c \in C$ from RPC $j \in J$ to RMP $u \in U$ in $t \in T$

T_{jx}^t Unit transportation cost of $c \in C$ from RPC $j \in J$ to RP $x \in X$ in $t \in T$

T_{jv}^t Unit transportation cost of $c \in C$ from RPC $j \in J$ to DC $v \in V$ in $t \in T$

Tf_{uh}^t Unit transportation cost of product from $u \in U$ to $h \in H$ in period $t \in T$

Decision Variables

xp_{ccj}^t Amount of used product shipped from $cc \in CC$ to RPC $j \in J$ in $t \in T$

x_{mnc}^t Amount of $c \in C$ shipped from node m to node n in the network in $t \in T$

xfp_{uh}^t Amount of product shipped from RMP $u \in U$ to SM $h \in H$ in $t \in T$

EI_{uc}^t Amount of $c \in C$ hold in inventory in RMP $j \in J$ in the end of $t \in T$

$$v_{cc}^t = \begin{cases} 1, \text{if collection center } cc \in CC \text{ is operating in period } t \in T \\ 0, \text{ oterwise} \end{cases}$$

$$y_j^t = \begin{cases} 1, \text{if RPC } j \in J \text{ is operating in period } t \in T \\ 0, \text{ oterwise} \end{cases}$$

$$z_j^t = \begin{cases} 1, \text{if RMP } u \in U \text{ is operating in period } t \in T \\ 0, \text{ oterwise} \end{cases}$$

MATHEMATICAL MODEL:

Minimize:

$$\sum_t \Big(\sum_{cc} f_{cc}^t (v_{cc}^t - v_{cc}^{t-1}) + \sum_j f_j^t (y_j^t - y_j^{t-1}) + \sum_u f_u^t (z_u^t - z_u^{t-1})\Big) + \sum_t \sum_j \Big(\sum_{cc} xp_{ccj}^t\Big) cdm_j^t + \sum_t \sum_c \sum_j \Big(\sum_s x_{jsc}^t + \sum_u x_{juc}^t\Big) cr_{jc}^t$$

$$+ \sum_t \sum_c \sum_v \Big(\sum_j x_{jvc}^t\Big) cdp_{vc}^t + \sum_t \sum_u \Big(\sum_h xfp_{uh}^t\Big) casm_u^t + \sum_t \sum_c \sum_u \sum_z x_{zuc}^t c_{zuc}^t + \sum_t \sum_c \sum_u EI_{uc}^t IC_{uc}^t + \sum_t \sum_{cc} \sum_j xp_{ccj}^t Tp_{ccj}^t$$

$$+ \sum_t \sum_s \sum_j \Big(\sum_c x_{jsc}^t\Big) TS_{js}^t + \sum_t \sum_u \sum_j \Big(\sum_c x_{juc}^t\Big) T_{ju}^t + \sum_t \sum_x \sum_j \Big(\sum_c x_{jxc}^t\Big) T_{jx}^t + \sum_t \sum_v \sum_j \Big(\sum_c x_{jvc}^t\Big) T_{jv}^t + \sum_t \sum_u \sum_h xfp_{uh}^t Tf_{uh}^t$$

Subject to:

$$\sum_j xp_{ccj}^t = Q_c^t \qquad \forall cc, t \qquad (1)$$

$$\sum_j x_{jsc}^t \le \sum_{cc} \sum_j xp_{ccj}^t - \sum_j \sum_v x_{jvc}^t - \sum_x \sum_j x_{jxc}^t \qquad \forall s, c, t \qquad (2)$$

$$\sum_j x_{jsc}^t \ge D_{sc}^t \qquad \forall s, c, t \qquad (3)$$

$$\sum_{cc} xp_{ccj}^t = \sum_s x_{jsc}^t + \sum_u x_{juc}^t + \sum_x x_{jxc}^t + \sum_v x_{jvc}^t \qquad \forall j, c, t \qquad (4)$$

$$\sum_u x_{juc}^t + EI_{uc}^{t-1} + \sum_z x_{zuc}^t = \sum_h xfp_{uh}^t + EI_{uc}^t \qquad \forall u, c, t \qquad (5)$$

$$\sum_{u} xfp_{uh}^{t} \geq D_{h}^{t} \qquad \forall h, t \qquad (6)$$

$$\sum_{cc} xp_{ccj}^{t} \leq cap_{j} \qquad \forall j, t \qquad (7)$$

$$\sum_{c}\sum_{s} x_{jsc}^{t} + \sum_{c}\sum_{u} x_{juc}^{t} \leq rcap_{j} \qquad \forall j, t \qquad (8)$$

$$\sum_{h} xfp_{uh}^{t} \leq pcap_{u} \qquad \forall u, t \qquad (9)$$

$$\sum_{c} EI_{uc}^{t} \leq icap_{u} \qquad \forall u, t \qquad (10)$$

$$\sum_{x}\sum_{j}\sum_{c} x_{jxc}^{t} = \rho * \sum_{j}\sum_{cc} xp_{ccj}^{t} \qquad \forall t \qquad (11)$$

$$\sum_{c}\sum_{j} x_{jxc}^{t} \leq reccap_{x} \qquad \forall x, t \qquad (12)$$

$$\sum_{v}\sum_{c}\sum_{j} x_{jvc}^{t} = \sigma * \sum_{j}\sum_{cc} xp_{ccj}^{t} \qquad \forall t \qquad (13)$$

$$\sum_{c}\sum_{j} x_{jvc}^{t} \leq discap_{v} \qquad \forall v, t \qquad (14)$$

$$Q_{c}^{t} \geq MTCC_{cc}^{t} * v_{cc}^{t} \qquad \forall cc, t \qquad (15)$$

$$\sum_{cc} xp_{ccj}^{t} \geq MTJ_{j}^{t} * y_{j}^{t} \qquad \forall j, t \qquad (16)$$

$$\sum_{h} xfp_{uh}^{t} \geq MTU_{u}^{t} * z_{u}^{t} \qquad \forall u, t \qquad (17)$$

$$v_{cc}^{t} \leq v_{cc}^{t+1} \qquad \forall cc, t \qquad (18)$$

$$y_{j}^{t} \leq y_{j}^{t+1} \qquad \forall j, t \qquad (19)$$

$$z_{u}^{t} \leq z_{u}^{t+1} \qquad \forall u, t \qquad (20)$$

$$xp_{ccj}^{t}, x_{jsc}^{t}, x_{juc}^{t}, x_{jxc}^{t}, x_{jvc}^{t}, x_{zuc}^{t}, xfp_{uh}^{t} \geq 0 \qquad \forall cc, j, s, u, x, v, c \qquad (21)$$

$$EI_{uc}^{t} \geq 0 \qquad \forall u, c, t \qquad (22)$$

$$v_{cc}^{t} \in \{0,1\} \qquad \forall cc, t \qquad (23)$$

$$y_{j}^{t} \in \{0,1\} \qquad \forall j, t \qquad (24)$$

$$z_{u}^{t} \in \{0,1\} \qquad \forall u, t \qquad (25)$$

Objective function of the above mathematical formulation is cost minimization. Costs incurred are the fixed costs of establishing facilities, operational (dismantling, processing, assembling and disposal) costs, transportation costs, inventory holding costs, and component purchasing costs. Constraints(1) shows that total amount of returned product collected at CC will shipped to the RPC which are to be located. At RPC, dismantled components can be directly sent to recycling or disposal sites and remaining components are shipped to spare market to satisfy the demand at spare market are shown via constraint (2) and (3). After satisfying demand at spare market components are send to RMP to assemble in the product form and if any shortages of the component occur would be purchased from supplier in order to satisfy the demand of secondary market is exposed via constraint (4), (5) and (6). Constraint (5) is the flow balance constraint for RMP. Total inflow, which is composed of components coming from inspection centers, components purchased from suppliers, and components in the inventory, must be equal to the outflow, which is composed of products sold to secondary markets, and the components to be held in inventory.

Constraint (7) ensures that the amount of products that are sent to RPC do not exceed the capacity of the collection center. Constraint (8) satisfy the reprocessing capacity constraint at RPC and (9) for the production capacity of RMP. Inventory to be held in the remanufacturing plants cannot exceed the inventory holding capacity via (10). (11), (12), (13) and (14) are for recycling and disposal capacity at recycling and disposal sites respectively. Constraints (15) - (17) are minimum throughput constraints guaranteeing that a CC, a RMP can only be established if the operation or production amount exceeds the predefined limits. (18) – (20) assure that once a facility is installed it remains operating until the end of the planning horizon. Lastly, Constraints (21)–(25) are domain constraints. The above problem is too complex and big. To get best possible solution we use differential Evolution algorithm.

4. Differential evolution

Differential Evolution (DE) was proposed by Price and Storn in 1995 to solve the polynomial fitting problem. DE is a small and simple mathematical model of a big and naturally complex process of evolution. It optimizes a problem by iteratively trying to improve a solution with regard to a given measure of quality. However, DE does not guarantee an optimal solution is ever found. DE optimizes a problem by maintaining a population of candidate solutions and creating new candidate solutions by combining existing ones, and then keeping whichever candidate solution has the best score or fitness on the optimization problem. The process is repeated and by doing so it is hoped, but not guaranteed, that a satisfactory solution will eventually be discovered. The basic DE Algorithm can be described as:

a) **Initialization**: All solution vectors in a population are randomly initialized. The initial NP, D-dimensional vectors $X_{i,G} = (x_{1,i,G}, x_{2,i,G}, x_{3,i,G}, \ldots, x_{D,i,G})$ are generated between lower and upper bounds $l = \{l_1, l_2, \ldots, l_D\}$ and $u = \{u_1, u_2, \ldots, u_D\}$ using the equation: $x_{j,i,0}=l_j+rand_{i,j}[0,1]*(u_j-l_j)$ where $rand_{i,j}[0,1]$ is uniformly distributed random number lying between 0 and 1.

b) **Mutation:** The mutation process at each generation begins by randomly selecting three individuals in the population. The i^th perturbed individual $V_{i,G}$ is therefore generated based on the three choosen individuals as follows: $V_{i,G}=X_{r1,G}+F*(X_{r2,G}-X_{r3,G})$ where $r1,r2,r3 \in \{1,\ldots\ldots,NP\}$ are randomly selected, such that $r1 \neq r2 \neq r3 \neq i$ and $F \in (0,1.2]$

c) **Crossover:** The perturbed individual, $V_{i,G} = (v_{1,i,G}, \ldots v_{D,i,G})$, and the current population member, $X_{i,G} = (x_{1,i,G}, x_{2,i,G}, x_{3,i,G}, \ldots, x_{D,i,G})$ are then subject to the crossover operation, that finally generates the population of candidates, or trial vector, $U_{i,G}=(u_{1,i,G}, \ldots, u_{D,i,G})$ as follows:

$u_{j,i.G} = \begin{cases} v_{j,i.G} & \text{if } rand_{i,j}[0,1] \le C_r \vee j = j_{rand} \\ x_{j,i.G} & \text{otherwise} \end{cases}$ where $C_r \in [0, 1]$, is crossover probability and $j_{rand} \in \{1, . . , D\}$ is a random parameter's index, for each i

d) **Selection**: The population for the next generation is selected from the individuals in current population and its corresponding trial vector according to the following rule: $X_{i.G+1} = \begin{cases} U_{i.G} & \text{if } f(U_{i.G}) \le f(X_{i.G}) \\ X_{i.G} & \text{otherwise} \end{cases}$ Each individual of the temporary population is compared with its counterpart in the current population. Trial vector is only compared to one individual, not to all the individuals in the current population. Where f ( ) is objective function.

e) **Constraint handling in differential evolution:** the Pareto ranking method was proposed by Deb, which is based on the following three:

i. Feasible solution with the best value of the objective function is preferred.

ii. Feasible one is preferred over infeasible.

iii. Infeasible vectors with the lowest sum of constraint violation are preferred.

f) **Stopping criteria:** there are two stopping criteria: Maximum number of generations and accuracy criteria.

5. Numerical illustration

Eight echelon network consisting of 4 CC, 3 RPC's, 3 RMP's, 5 spare markets , 1 RC, 1 DS, 6 new module suppliers and 6 distribution centers has been considered for the model implementation. 50% of returned modules of the returned products are assumed to be disposed. Good modules are either sent to the factory for remanufacturing, or to spare market. 30% of the returned modules are assumed to be sent for recycling. Single returned products with 10 modules are considered. Data used for the analysis are given as: Minimum throughput required for collection center, RPC, and RMP are {4000, 4000, 5000, 5000}, {5000, 3000, 7000} and {1000, 1500, 1000} resp. Apart from that capacities of storage, processing of RPC's are {9350, 6700, 5500} and {70000, 40000, 90000} resp. Production capacities of RMPs are {7000, 6500, 6500}. Capacity of recycling center and disposal site are 50000 and 90000 resp.

Table 1 Data on costs and demand in the network

	Period 1	**Period 2**	**Period 3**	**Period4**	**Period 5**
Set up cost of CC(cc1,..,cc4)	5750,5500, 4900,6900	5800,5600 4970,7000	5850,5660 5000,7100	5930,6000, 5100,7100	5950,6200, 5100,7300
Set up cost of RPC j1..j3	9350,6700, 5500	9400,6740, 5640	9480,6790, 5700	9500,6820, 5730	9550,6850, 5750
Set up cost of RMP u1,u2,u3	4850,4550, 4600	4900,4600, 4640	4930,4600, 4650	4950,4640, 4670	4970,4650, 4680
Dismantling at RPC(j1,j2,j3)	18,16,14	18.5,16.3,14.7	18.9,17,15.2	19.1,17.3,15.2	19.5.17.5,15.5
Assembling cost at u1,u2,u3	34,35.6,34.8	34.3,35.8,35	34.5,35.9,35.3	34.8,36.1,35.2	35,36.4,35.5
Disposal cost of c1,….,c10 at disposal site	.99,1.08,1.64,.0 86,2.27,3.58,2.2 5,1.03,2.09,1.78	1.11,1.23,1.8,0.98, 2.39,3.7,2.37,1.15, 2.21,1.9	1.34,1.46,2.03,1.2 1,2.62,3.93,2.6,1.3 8,2.44,2.13	1.43,1.55,2.12,1.3, 2.71,4.02,2.69,1.4 7,2.53,2.22	1.57,1.69,2.26,1.4 4,2.85,4.16,2.83,1. 61,2.67,2.36
Processing cost of c1,…,c10 at RPC j1	0.64,0.58,0.16,0 .36,0.3,0.48,0.5, 0.58,1.04,1	0.88,0.82,0.4,0.6,0 .54,0.72,0.74,0.82, 1.28,1.24	1.06,1,0.58,0.78,0. 72,0.9,0.92,1,1.46, 1.42	1.30,1.24,0.82,1.0 2,0.96,1.14,1.16,1. 24,1.7,1.66	1.43,1.37,0.95,1.1 5,1.09,1.27,1.29,1. 37,1.83,1.79
Processing cost	0.68,0.64,0.24,0	0.92,0.88,0.48,0.5	1.1,1.06,0.66,0.71,	1.34,1.30,0.9,0.95,	1.47,1.43,1.03,1.0

of c1,…..,c10at RPC j2	.29,0.29,0.48,0.6,0.52,0.88,0.76	3,0.53,0.72,0.84,0.76,1.12,1	0.71,0.9,1.02,0.94,1.3,1.18	0.95,1.14,1.26,1.18,1.54,1.42	8,1.08,1.27,1.39,1.31,1.67,1.55
Processing cost of c1,…,c10at RPC j3	0.66,0.62,0.2,0.31,0.28,0.45,0.55,0.55,0.92,0.84	0.9,0.86,0.44,0.55,0.52,0.69,0.79,0.79,1.16,1.08	1.08,1.04,0.62,0.73,0.7,0.87,0.97,0.97,1.34,1.26	1.32,1.28,.86,0.97,0.94,1.11,1.21,1.21,1.58,1.50	1.45,1.41,0.99,1.10,1.07,1.24,1.34,1.34,1.71
Demand at h1,….,h6	3500,3500,2500 3500,2500,2500	3550,3600,2700 3600,2600,2550	3600,3520,2600, 3580,2600,2600	3600,3550,2600 3600,2700,2700	3610,3520,2700 3620,2650,2700
Demand at spare market s1 for c1,…,c10	2400,600,1000 3500,1200,425,1000,0,500,2300	2430,630,1030,3530,1230,4280,1000,0,520,2320	2460,660,1080,3570,1260,4300,1050,0,550,2320	2580,800,1150,3680,1350,4450,1150,1100,600,2400	2550,800,1150,3980,1300,4360,1350,1000,700,2550
Demand at spare market s2 for c1,…c10	0,3500,2500,0,3500,1900,0,2000,600,0	0,3520,2540,0,3530,1950,1010,2040,630,0	0,3510,2520,0,3550,1950,0,2030,650,0	0,3580,2600,900,3300,1600,0,300,600,0	0,3600,2500,930,3500,1750,0,200,500,0
Demand at spare market s3 for c1,…,c10	2500,2500,2400,1500,2000,800,1500,2500,900,2400	2580,2540,2460,1550,2060,830,1220,2530,980,2430	2570,2550,2460,1550,2060,830,1520,2530,980,2430	2400,2300,2360,1500,2200,800,1400,2300,880,2500	2470,2200,2360,1400,2100,900,1300,2280,880,2200
Demand at spare market s4 for c1,…,c10	2000,550,1800,2700,800,100,1800,1500,4000,1850	2020,570,1850,2730,830,1020,1430,1550,4030,1870	2430,590,1870,2750,830,1020,1830,1550,4030,1900	2100,600,1600,2800,750,1050,1990,1350,3950,1600	2000,550,1630,2700,830,1090,1890,1300,4000,1500
Demand at spare market s5 for c1,…,c10	0,1850,1500,0,800,800,4100,500,1500,950	0,1880,1530,0,820,830,3820,550,1530,970	0,1880,1530,0,850,830,4120,550,1530,970,	0,1800,1400,0,800,700,4100,400,1400,900	0,1900,1400,0,1000,800,4100,400,1400,900

Table 2 data on transportation cost/unit of product or component

	Period 1	Period 2	Period 3	Period4	Period 5
From cc1 to j1,j2,j3	0.95,0.83,0.9	0.97,0.85,0.92	1,0.89,0.95	1.04,0.93,0.99	1.08,0.99,1.02
From cc2 to j1,j2,j3	1.11,1.05,1.02	1.17,1.09,1.08	1.20,1.12,1.12	1.23,1.16,1.18	1.27,1.2,1.22
From cc3 to j1,j2,j3	1.16,1.19,1.23	1.19,1.23,1.27	1.23,1.27,1.31	1.28,1.31,1.34	1.32,1.34,1.37
From cc4 to j1,j2,j3	0.87,0.77,0.83	0.91,0.80,0.87	0.95,0.84,0.90	0.99,0.87,0.95	1.03,0.9,0.99
From j1 to u1,u2,u3	0.24,0.23,0.24	0.26,0.25,0.27	0.28,0.28,0.29	0.3,0.31,0.32	0.33,0.34,0.35
From j2 to u1,u2,u3	0.21,0.24,0.23	0.24,0.27,0.25	0.26,0.29,0.27	0.29,0.33,0.29	0.32,0.35,0.31
From j3 to u1,u2,u3	0.24,0.22,0.23	0.26,0.25,0.25	0.29,0.28,0.26	0.31,0.32,0.28	0.33,0.34,0.3
From j1,j2,j3 to RP	4.65,2.8,3.35	4.95,3,3.55	5.2,3.2,3.8	5.56,3.5,4	5.80,3.75,4.25
From j1,j2,j3 to DS	2.25,2.75,2.2	2.4,2.9,2.55	2.75,3,2.80	2.9,3.25,3	3.1,3.55,3.35
From j1to s1,..,s5	0.9,0.75,0.89,0.78,0.81	0.92,0.78,0.91,0.83,0.88	0.93,0.8,0.94 0.83,0.85	0.95,0.82,0.96,0.85,0.88	0.99,0.84,0.99 0.88,0.9
From j2 to s1,…,s5	0.86,0.84,0.86,0.75,0.78	0.88,0.86,0.89,0.79,0.81	0.9,0.88,0.91,0.80,0.85	0.93,0.90,0.93,0.82,0.86	0.95,0.94,0.96,0.85,0.88
From j3 to s1,…,s5	0.89,0.8,0.87,0.78,0.78	0.92,0.85,0.90’0.8,0.81	0.94,0.87,0.91,0.82,0.82	0.96,0.9,0.94,0.85,0.84	0.98,0.92,0.97,0.88,0.89
From u1 to h1,…,h6	1.59,3.18,2.85,0.78,1.71,2.43	1.8,3.39,3,0.9,1.99,2.6	2.06,3.7,3.25,1.23,2.23,2.83	2.28,3.89,3.65,1.58,2.73,2.9	2.59,4,3.95,1.88,2.99,3.26
From u2 to h1,..,h6	2.52,2.4,2.28,0.75,1.47,2.73	2.72,2.65,2.56,1,1.77,2.93	2.92,2.88,2.76 1.25,1.96,3.32	3.33,3.12,2.99 2.59,2.26.3.52	3.58,3.46,3.35 2.86,2.45,3.78
From u3 to h1…,h6	2.1,2.07,2.58,0.78,1.89,2.79	2.55,2.48,2.8,1.1,1,2.99	2.95,2.62,3.05,1.26,1.18,3.3	3.22,2.85,3.35 1.56,1.48,3.75	3.68,3,3.75,1.86,1.68,3.94

Table 3 Data on cost of purchased components/unit

	Period 1	Period 2	Period 3	Period4	Period 5
From z1 to RPC u1	3,6.25,11.25,5.3,6.6,6.85,13.3,7.45,5.75,8.25	3.2,6.45,11.45,5.5,6.8,7.05,13.5,7.65,5.95,8.45	3.39,6.65,11.45,5.65,6.95,7.24,13.95 7.84,6.14,8.64	3.55,6.8,11.81,5.85,7.11,7.4,13.7,8 6.3,8.8	3.91,7.2,12.22,6.25,7.53,7.81,14.26,8.43,6.75,9.22
From z1 to RPC u2	3.3,6.5,11.5,5.6,6.8,7.05,13.5,7.65,6,8.75	3.5,6.7,11.7,5.8,7,7.25,13.7,7.85,6.2,8.95	3.69,6.89,11.85,5.99,7.19,7.44,13.85,8.04,6.39,9.19	3.8,7.05,12.06,6.18,7.33,7.61,14.03,8.2,6.57,9.34	4.26,7.47,12.44,6.54,7.77,8,14.46,8.61,6.95,9.73
From z1 to RPC u3	3.2,6.4,11.35,5.75,6.25,6.5,13.35,7.5 5.6,8.25	3.4,6.6,11.55,5.95,6.45,6.7,13.55,7.7,5.8,8.45	3.59,6.79,11.74,6.14,6.69,6.99,13.74,7.89,5.99,8.64	3.77,6.95,11.92,6.35,6.83,7.05,13.9,8.05,6.09,8.81	4.15,7.36,12.3,6.73,7.22,7.45,14.35,8.45,6.55,9.26
From z2 to RPC u1	3.2,6.45,11.45,5.5,6.8,7.05,13.5,7.65,5.95,8.45	3.4,6.65,11.65,5.7,7,7.25,13.7,7.85,6.15,8.65	3.95,6.89,11.45,5.8,7.19,7.45,13.95,8.45,6.35,8.85	3.75,7,12.09,6.03,7.3,7.63,14.05,8.2,6.56,9	4.15,7.42,12.45,6.46,7.77,8.03,14.47,8.6,6.9,9.4
From z2 to RPC u2	3.5,6.7,11.7,5.8,7,7.25,13.7,7.85,	3.7,6.9,11.9,6,7.2,7.45,13.9,8.05,	3.85,7.09,12.05,6.19,7.39,7.64,14.05	4.03,7.22,12.23,6.34,7.55,7.8,14.25,	4.45,7.65,12.66,6.77,7.95,8.2,14.63,

	6.2,8.95	6.4,9.15	,8.24,6.59,9.34	8.41,6.7,9.5	8.8,7.15,9.9
From z2 to RPC u3	3.4,6.6,11.55,5.95, 6.45,6.7,13.55,7.7 5.8,8.45	3.6,6.8,11.75,6.15, 6.65,6.9,13.75,7.9' 6,8.65	3.79,6.95,11.95,6. 35,6.85,7.05,13.95 ,8.05,6.15,8.87	3.92,7.13,12.1,6.5 1,7.01,7.22,14.13, 8.22,6.36,9.01	4.36,7.57,12.53,6. 9,7.4,7.656,14.5,8. 65,6.76,9.4
From z3 to RPC u1	3.4,6.65,11.65,5.7, 7,7.25,13.7,7.85,6. 15,8.65,	3.6,6.85,11.85,5.9, 7.2,7.45,13.9,8.05, 6.35,8.85	3.76,7.04,12.05,6. 12,7.39,7.64,14.15 ,8.24,6.63,9.26	3.9,7.2,12.22,6.26, 7.53,7.8,14.26,8.4 1,6.72,9.23	4.35,7.61,12.62,6. 66,7.95,8.2,14.63, 8.8,7.1,9.6
From z3 to RPC u2	3.7,6.9,11.9,6,7.2, 7.45,13.9,8.05,6.4 ,9.15	3.9,7.1,12.1,6.2, 7.4,7.65,14.1,8.25, 6.6,9.35	4.09,7.29,12.23,6. 39,7.57,7.84,14.22 ,8.44,6.79,9.54	4.25,7.46,12.4,6.5, 7.7,8,14.4,8.6,6.9, 9.71	4.65,7.86,12.86,6. 96,8.17,8.4,14.83, 9,7.35,10.1
From z3 to RPC u3	3.6,6.85,11.85,5.9, 7.2,7.45,13.9,8.05, 6.35,8.85	3.8,7,11.95,6.35, 6.85,7.1,13.95,8.1 ,6.2,8.85	3.99,7.19,12.13,6. 54, .04,7.29,14.15, 8.26,6.39,9.04	4.15,7.35,12.33,6. 71,7.22,7.43,14.35 ,8.46,6.5,9.2	4.55,7.75,12.7,7.1, 7.6,7.85,14.7,8.85, 6.93,9.6
From z4 to RPC u1	3.6,6.85,11.85,5.9 7.2,7.45,13.9,8.05, 6.35,8.85	3.8,7.05,12.05,6.1, 7.4,7.65,14.1,8.25, 6.55,9.05	3.92,7.23,12.24,6. 25,7.58,7.84,14.27 ,8.46,6.73,9.24	4.15,7.45,12.95,6. 45,7.76,8.01,14.49 ,8.6,6.92,9.43	4.5,7.8,12.3,6.8,8. 1,8.43,14.85,9,7.3, 9.8
From z4 to RPC u2	3.9,7.1,12.1,6.2,7. 4,7.65,14.1,8.25,6. 6,9.35	4.1,7.3,12.3,6.4, 7.6,7.85,14.3,8.45 ,6.8,9.55	4.29,7.49,12.35,6. 95,7.83,8.03,14.48 ,8.64,6.99,9.74	4.49,7.66,12.64,6. 75,7.9,8.2,14.76,8. 8,7.15,9.9	4.8,8.05,13,7.15,8. 35,8.6,15,9.2,7.53, 10.3
From z4 to RPC u3	3.8,7,11.95,6.35,6. 85,7.1,13.95,8.1,6. 2,8.85	4,7.2,12.15,6.55, 7.05,7.3,14.15, 8.3,6.4,9.05	4.19,7.39,12.35,6. 74,7.24,7.49,14.35 ,8.48,6.5,9.24	4.35,7.5,12.68,6.8 7,7.4,7.63,14.52,8. 63,6.78,9.43	4.75,7.96,12.9,7.3, 7.8,8.05,14.9,9.05, 9.05,7.15,9.8
From z5 to RPC u1	3.8,7.05,12.05,6.1, 7.4,7.65,14.1,8.25, 6.55,9.05	4,7.25,12.25,6.3, 7.6,7.85,14.3,8.45, 6.75,9.25	4.20,7.45,12.35,6. 47,7.75,8.05,14.45 8.64,6.93,9.44	4.35,7.6,12.7,6.65, 7.95,8.23,14.67,8. 82,7.1,9.61	3.94,7.19,12.18,6. 24,7.55,7.79,14.24 ,8.39,6.69,9.19
From z5 to RPC u2	4.1,7.3,12.3,6.4,7. 6,7.85,14.3,8.45,6. 8,9.55	4.3,7.5,12.5,6.6 7.8,8.05,14.5,8.65, 7,9.75	4.47,7.66,12.64,6. 78,7.98,8.24,14.62 ,8.83,7.18,9.95	4.63,7.87,12.8,6.9 5,8.1,8.45,14.85,9, 7.35,10.1	4.25,7.46,12.47,6. 54,7.74,7.99,14.5, 8.6,6.95,9.7
From z5 to RPC u3	4,7.2,12.15,6.55, 7.05,7.3,14.15,8.3, 6.4,9.05	4.2,7.4,12.35,6.75, 7.25,7.5,14.35,8.5, 6.6,9.25	4.39,7.53,12.54,6. 93,7.42,7.67,14.54 ,8.69,6.77,9.48	4.55,7.76,12.71,7. 12,7.62,7.85,14.7, 8.85,6.95,9.6	4.14,7.35,12.3,6.6 9,7.2,7.45,14.31,8. 44,6.54,9.19
From z6 to RPC u1	4,7.25,12.25,6.3,7. 6,7.85,14.3,8.45,6. 75,9.25	4.2,7.45,12.45,6.5, 7.8,8.05,14.5,8.65 6.95,9.45	4.31,7.64,12.62,6. 69,7.93,8.24,14.64 ,8.85,7.14,9.64	3.76,7,12.3,6.03,7. 33,7.63,14.14,8.2, 6.5,9	4.15,7.39,12.4,6.4 5,7.76,7.99,14.47, 8.6,6.9,9.39
From z6 to RPC u2	4.3,7.5,12.5,6.6,7. 8,8.05,14.5,8.65,7, 9.75	4.5,7.7,12.7,6.8, 8,8.25,14.7, 8.85,7.2,9.95	4.69,7.86,12.87,6. 99,8.2,8.45,14.8, 9.04,7.39,10.14	4.05,7.24,123.22,6 .33,7.51,7.8,14.25, 8.42,6.76,9.5	4.44,7.66,12.6,6.7 4,7.95,8.2,14.66,8. 8,7.17,9.91
From z6 to RPC u3	4.2,7.4,12.35,6.75, 7.25,7.5,14.35,8.5, 6.6,9.25	4.4,7.6,12.55,6.95 7.45,7.7,14.55, 8.7,6.8,9.45	4.6,7.8,12.74,7.09, 7.63,7.88,14.74 8.89,6,9.64	3.95,7.15,12.1,6.5, 7,7.25,14.13,8.25, 6.3,9	4.35,7.54,12.49,6. 9,7.4,7.64,14.5,8.6 4,6.74,9.56

The proposed model with the above data is solved through differential algorithm with a population size of 3000 and with the value .5 for scaling factor (f) and .6 as crossover probability (C). Resultant values of the variable is listed in the tables below

Table 4 Solution table

	Period 1	Period 2	Period 3	Period4	Period 5
v(cc1…cc4)	1,1,0,1	1,1,0,1	1,1,0,1	1,1,0,1	1,1,0,1
y(j1,j2,j3)	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1
Z(u1,u2,u3)	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1

Table 5 no of units of returned product shipped from CC to RPC

	Period 1	Period 2	Period 3	Period4	Period 5
cc1- j1..j3	1360,4630,2010	1749,4651,1900	7778,5720,6950	0,0,8400	0,0,8470
cc2- j1..j3	6990,0,0	0,0,7100	0,4150,0	6550,0,600	6660,0,530
cc3 - j1..j3	6000,0,0	6300,0,0	0,0,2050	1436,4663,0	1476,4654,0

Table 6 quantity of components shipped from RPCs to spare market in period 1…5

	s1	s2	s3	s4	s5
c1- j1||j2 || j3	0,0,0,0,844||0,0,0,0 ,0||2400,2430,2460 ,2580,1706	0,0,0,0,0||0,0, 0,0,0||0,0,0,0, 0	0,0,0,0,0||0,0,0,0,0||2 500,2580,2570,2400, 2470	2000,0,0,0,200||0,0, 0,0,0||0,2020,2030, 2100,0	0,0,0,0,0|| 0,0,0,0,0|| 0,0,0,0,0

c2- j1 ||j2||j3	0,0,0,0,0|| 600,630,660,800,800||0,0,0,0,0	3500,3520,3510,3580,2068||0,0,0,0,0||0,0,0,0,1532	0,0,0,0,0||2490,2491,2550,2300,2200||10,49,0,0,0	0,0,0,0,0||550,570,590,600,550||0,0,0,0,0	0,0,0,0,0||0,0,0,0,1104||1850,1880,1888,1800,796
c3- j1|| j2|| j3	0,0,0,0,0||1000,1030,1080,115 0,1150||0,0,0,0,0	2500,2540,2520,2600,2500||0,0,0,0,0||0,0,0,0,0	0,0,0,0,0||1040,2460,1490,1260,474||1360,0,970,1100,1886	0,0,0,0,0||1800,880,1870,1600||630,0,970,0,0,0	0,0,0,0,0||0,0,0,0,1400||1500,1530,1530,1400,0
c4- j1|| j2|| j3	0,0,1386,1817,0||3500,3530,2184,1863,3980||0,0,0,0,0	0,0,0,900,930||0,0,0,0,0||0,0,0,0,0	0,659,0,0,0||0,891,0,0,0||1500,0,1550,1540 0,1400	2700,0,0,0,2029||0,230,1800,2800,671||0,2500,950,0,0	0,0,0,0,0||0,0,0,0,0||0,0,0,0,0
c5- j1||- j2|| j3	0,0,0,0,0||1200,1230,1260,1350,1300||0,0,0,0,0	3500,3530,3550,3300,3500||0,0,0,0,0||0,0,0,0,0	0,0,0,0,0||0,0,0,0,1524||2000,2060,2060,2200,576	0,0,0,0,0||800,0,0,750,830|| 0,830,830,0,0	0,0,0,0,0||0,0,0,0,1000||800,820,850,800,0
c6- j1|| j2|| j3	0,0,0,837,0||3630,4280,4300,3613,3564||620,0,0,0,796	1900,1950,1950,1600,1750||0,0,0,0,0||0,0,0,0,0	0,0,0,0,0||0,0,0,0,0||800,830,830,800,900	0,0,0,0,0||1000,0,0,1050,1090||0,1020,1020,0,0	0,0,0,0,0||0,0,0,0,0||800,830,830,700,800
c7- j1|| j2|| j3	0,0,0,1150,0||1000,1000,1050,0,1350||0,0,0,0,0	0,1010,0,0,0||0,0,0,0,0||0,0,0,0,0	0,0,0,0,0||240,1220,0,1400,1300||1260,0,1520,0,0	0,0,0,0,0|| 1800,1430,1830,1990,1890|| 0,0,0,0,0	0,319,0,0,1486||0,0,0,0,114||4100,3501,4120,4100,2500
c8- j1|| j2|| j3	0,0,0,0,0||0,0,0,1100,1000||0,0,0,0,0,0	2000,2040,2030,300,200||0,0,0,0,0||0,0,0,0,0	0,909,0,0,0||0,1221,580,200,1954|| 2500,400,1950,2100,326	0,0,0,0,0||1500,0,1550,1350,1300||0,1550,0,0,0	0,0,0,0,0||0,0,0,0,400||500,550,550,400,0
c9- j1||- j2|| j3	0,0,0,600,0||500,520,550,0,700|| 0,0,0,0,0	600,630,650,600,500||0,0,0,0,0||0,0,0,0,0	0,0,0,0,0||0,0,0,0,0||900,980,980,880,880	4000,0,0,0,1265||0,0,2412,2696,2735||0,4030,1618,1254	0,0,0,0,0||0,0,0,0,0||1500,1530,1530,1400,1400
c10- j1|| j2|| j3	0,0,0,237,0||2300,2320,2320,2163,2550||0,0,0,0,0	0,0,0,0,0||0,0,0,0,0||0,0,0,0,0	0,439,0,0,0||0,461,502,900,0||2400,1530,1928,1600,2200	1850,0,0,0,60 0||1870,1900,1600,1440||0,0,0,0,0	0,0,0,0,0||0,0,0,0,0||950,970,970,900,900

Table 7 Units of returned product shipped from RPC to secondary market

	Period 1	Period 2	Period 3	Period4	Period 5
u1 to h1…h6	3500,0,0,500, 500,2500,	3550,0,0,900, 0,2550	3600,0,0,800 0,2600	3600,0,0,700, 0,2700	3610,0,0,690, 0,2700
u2 to h1…h6	0,0,2500,0,2000 0	0,0,2700,2400, 0,0	0,0,2600,2400 0,0	0,2650,2600,0 0,0	0,2600,2700,0 0,0
u3 to h1…h6	0,3500,0,3000 0,0	0,3600,0,300, 2600,0	0,3520,0,380 2600,0	0,900,0,2900, 2700,0	0,920,0,2930,2650 0

Table 8: quantity of components shipped from RPCs to RMPs in the planning horizon

	u1	u2	u3
c1- j1	0,0,0,0,0	400,0,0,0,0	1360,0,0,0,0
c1- j2	0,0,0,0,0	0,0,0,0,0	0,0,0,0,0
c1- j3	0,0,0,0,	4100,1970,1940,1920,0	0,0,0,0,0
c2- j1	0,0,0,0,0	3860,4529,4268,2524,0	0,0,0,0,0
c2- j2	990,960,810,0,0,	0,0,0,0,0	0,0,112,963,0
c2- j3	0,0,0,0,0	640,571,732,2726,5300	6500,6500,6388,4474,1372
c3- j1	0,409,258,137,950	0,5100,5000,5250,4686	4860,0,0,0,0
c3- j2	790,281,282,653,0	0,0,0,0,0	0,0,0,0,0
c3- j3	0,0,0,0,0	4500,0,0,0,614	1640,6500,6500,6500,6500
c4- j1	1009,0,1390,20,977	0,4949,5000,5250,4200	3651,0,0,0,0
c4- j2	1127,0,0,0,0	0,0,0,0,0	0,0,0,0,0
c4- j3	0,0,0,1000,0	4651,0,0,0,1100	2849,6500,6500,6500,6500
c5- j1	3860,0,3538,0,4636	0,4519,690,4687,0	0,0,0,0,0
c5- j2	2630,3421,3462,2563,0	0,0,0,0,0	0,0,0,0,0
c5- j3	510,3579,0,4437,2364	4500,581,4310,563,5300	1190,1130,950,1000,760
c6- j1	5460,6099,5828,5550,6386	0,0,0,0,0	0,0,0,0,0
c6- j2	0,371,422,0,0	0,0,0,0,0	0,0,0,0,0
c6- j3	1540,530,750,1450,614	4500,5100,5000,5250,5300	740,690,570,800,590
c7- j1	0,16320,5158,1260,1350	860,5100,2620,5250,5300	6500,0,0,327,0

c7- j2	1590,0,1842,0,0	0,0,0,0,0	0,1001,0,1273,0
c7- j3	0,0,0,0,0	3640,0,2380,0,0	0,5499,980,4900,6500
c8- j1	360,0,748,2437,4810	0,5100,5000,5250,3126	5000,0,0,0,0
c8- j2	3130,3430,2592,2013,0	0,0,0,0,0	0,0,0,0,0
c8- j3	0,0,0,0,0	4500,0,0,0,2174	1500,6500,6500,6500,6500
c9- j1	2760,2319,7000,6787,1071	0,5100,128,0,5300	0,0,0,0,0
c9- j2	2463,2272,0,0,0	0,0,0,0,0	0,0,0,0,0
c9- j3	1777,2409,0,213,5929	4500,0,4872,5250,0	323,51,0,3,791
c10- j1	160,2510,2778,2500,7000	4500,5100,5000,5250,1076	850,0,0,0,0
c10- j2	2330,0,0,0,0	0,0,0,0,0	0,0,0,0,0
c10- j3	0,0,0,0,0	0,0,0,0,4224	5650,6500,6102,6500,6500

Quantity of components sent to recycling center in period 1,2,3,4 and 5 are 6297, 6510, 6450, 6495 and 6537 respectively and to disposal site are 10495, 10850, 10750, 10825 and 10895 respectively. Requirement of new components for remanufacturing to satisfy the demand of secondary market is as follows:
In period 1: 7000, 6010, 6210, 4864, 0, 0, 5410, 3510, 0, 4510 units of c1….c10 are purchased by RMP1 from supplier z1. 5140, 5310, 5760, 6177 units of c1, c5, c6 and c9 are purchased by RMP3 from suppler z1. **In period 2:** RMP1 purchased 7000, 6040, 6310, 7000, 5380, 3570, 4490 units of c1, c2, c3, c4, c7, c8 and c10 resp., RMP2 purchased 3130 units of c1 from z1 and RMP3 purchased 6500,5370,5810and 6449 units of c1, c5, c6 and c9 resp. from z1. **In period 3:** RMP1 purchased 7000, 6190, 5610, 3660, 4222 units of c1, c2, c4, c8 and c10 resp. from supplier1, RMP2 purchased 3060 units of c1, RMP3 purchased 6500,5550,5930,5520, 6500, and 3989 units of c1, c5, c6, c7, c9 and c10 resp. from z1, and RMP1 purchased 6460 units of c3 from z2. **In period 4:** RMP1 purchased 7000, 7000, 6210, 5980, 5740, 2550, and 4500 units of c1, c2, c3, c4, c7, c8, and c10 from z1,. RMP2 purchased 3300 units of c1from z1. RMP3 purchased 6550, 1063, 5500, 5700, 6497 units of c1, c2, c5, c6 and c9 from z1. **In period 5:** RMP1 purchased 7000 units of c1from z1. RMP1 purchased 7000, 6050, 6023, 5650, 2190 units of c2, c3, c4, c7 andc8 resp. from z5. RMP2 purchased 5300 units of c1from z5. RMP3 purchased 6500, 5128, 5740, 5910, 5709 units of c1, c2, c5, c6 and c9 from z5.

6 Conclusion

In this paper, we proposed a mathematical programming framework for multi-period reverse logistics network design problems of single returned used product. To satisfy the demand of remanufactured products there is a mix and match of old and new components. Therefore, the model incorporates an echelon for suppliers that can provide new components. Model also considers the demand of components in the spare market as it would generally fetch higher value per module for the companies. Decisions to be made regarding the location of the collection centers, RPC and RMP, capacity of the facilities, flow routing through the network, the amount of inventory held and the amount of components to be purchase from the suppliers by RMP's. With advancement in technology and design processes, it is possible to estimate the number and type of components that might have to be disposed. Therefore, we have assumed certain percentages of components going to recycling and disposal centers. Model brings out an important conclusion that, transportation and other logistics costs may not be an important factor in the design of a network.

Rather, the cost of reprocessing, remanufacturing, and the cost of new modules can be the driving factor for the choice of a reverse logistics network. A natural extension to the setting considered in this paper regards the inclusion of uncertainty issues. This is a relevant aspect in many practical reverse logistics planning problems.

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