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A Novel Sustainable Closed-loop Supply Chain Network Design by Considering Routing and Quality of Products

S. H. Mirmohammadi, R. Sahraeian*

College of Engineering, Department of Industrial Engineering, Shahed University, Tehran, Iran

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ABSTRACT

One of the strategic decisions that can be made in supply chain is designing its network which has high impact on costs, and satisfaction level of customers. This paper focuses on designing a distribution network including determining the number and location of facilities, how to allocate the customers in network, and also determining the extent of carrying different products from different origins to different destinations; in this distribution network, according to the existing restrictions, customer demand is considered at minimum cost. In addition to secondary chain and reuse market as a retrieval option, model flexibility in defining quality and routing-locating is also among the innovation points of the model. Firstly, in forward chain the model consists of supplier, manufacturer, warehouse, distributor, and customer. In reverse chain, the model includes reuse market, secondary supply chain, collection, reprocess and disposal centers. The model could be generalized to industries with various strategies. Secondly, a sensitivity analysis was performed on a numerical example; also the non-dominated sorting algorithm (NSGA II) was used for a large-sized sample; which its performance was measured by analysis of variance (ANOVA) test. The results show that, returned products with average quality lead to lower costs and higher social benefits; and meta-heuristic NSGA II method is efficient. Because, it creates business opportunities and leads to less economic and environmental costs.

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NOMENCLATURE

PARAMETERS		qu_{rem}	Minimum quality required for reprocessing
k	vj_q	qu_{rec}	Minimum quality required for recycling
P	vj_i	vc_{qa}	Operational cost of warehouse q for product *a*
Q	vj_m	vc_{ia}	Operational cost of distributor i for product *a*
I	vj_n	vc_{ma}	Operational cost of collector m for product *a*
J	vj_l	vc_{na}	Operational cost of reprocessor n for product *a*
M	vl_{pa}	vc_{la}	Operational cost of disposal center l for product *a*
N	vl_q	vj_{pa}	Number of jobs created due to producing a unit of product *a* by producer p
L	vj_{pa}	vj_q	Number of jobs created due to working at warehouse q
O	set of reuse markets (o=1,…,O)	vj_i	Number of jobs created due to working at distributor i
S	set of secondary supply chain (s=1,…,S)	vj_m	Number of jobs created due to working at collector m
C	set of raw materials (c=1,…,C)	vj_n	Number of jobs created due to working at reprocessor n
A	set of products (a=1,…,A)	vj_l	Number of jobs created due to working at destruction center l
V	set of vehicle types (v=1,…,V)	vl_{pa}	Lost days due to job losses during produce product *a* by producer p
SETS		vl_q	Lost days due to job losses during operations at warehouse q
cap_k	Maximum capacity of supplier k	vl_i	Lost days due to job losses during operations at distributor i
cap_p	Maximum capacity of producer p	vl_m	Lost days due to job losses during operations at collector m

*Coresponding Author Email: *sahraeian@shahed.ac.ir* (R. Sahraeian)

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cap_q	Maximum capacity of warehouse q	vl_n	Lost days due to job losses during operations at reprocessor n
cap_i	Maximum capacity of distributor i	vl_l	Lost days due to job losses during operations at destruction center l
cap_m	Maximum capacity of collector m	vol_a	Volume of a unit of product *a*
cap_n	Maximum capacity of reprocessor n	vol_c	Volume of a unit of raw *c*
cap_l	Maximum capacity of disposal center l	α_{ja}	The rate of returns from customer zone j for product *a*
cap_v	Maximum capacity of vehicle v	γ_n	Percentage of products sent from reprocessing center n to producers
c_{xyv}	Transportation cost from facility *x* to facility *y* with vehicle v, $x,y \epsilon \{k,p,q,i,j,m,n,l,o,s\}$, $x \neq y$	C_{ac}	Number of raw material c in BOM of product *a*
cp_v	Cost of vehicle rent v	vol_a	Volume of a unit of product *a*
d_{ja}	Demand of customer zone j for product a	**DECISION VARIABLES**	
eo_{pa}	Environmental effects of producing a unit of product *a* by producer p	N_{mlv}	Number of vehicle v from collector m to destruction center l
eo_q	Environmental effects of establishing warehouse q	N_{msv}	Number of vehicle v from collector m to secondary supply chain
eo_i	Environmental effects of establishing distributor i	H_{pa}	The amount of producing production a by producer p
eo_m	Environmental effects of establishing collector m	RA_{ja}	The amount of returned product a suitable for repairing
eo_n	Environmental effects of reprocessing reprocessor center n	RB_{ja}	The amount of returned product a suitable for reprocessing
eo_l	Environmental effects of disposing destruction center l	RC_{jt}	The amount of returned product a suitable for recycling
et_{xyv}	Environmental effects of transportation from facility *x* to facility *y* with vehicle v, $x,y \epsilon \{k,p,q,i,j,m,n,l,o,s\}$, $x \neq y$	RD_{ja}	The amount of returned product a suitable for destruction
fc_p	Fixed cost of producing by producer p	$\sigma_k = \{0,1\}$	If supplier k chosen, it gets value 1 and 0 otherwise
fc_q	Fixed cost of establishing warehouse q	$y_i = \{0,1\}$	If distribution *i* chosen, it gets value 1 and 0 otherwise
fc_i	Fixed cost of establishing distributor i	$y_q = \{0,1\}$	If warehouse *q* chosen, it gets value 1 and 0 otherwise
fc_m	Fixed cost of establishing collector m	SM_{kpc}	Number of raw material *c* shipped from supplier k to producer p
fj_q	Number of jobs created due to establishing warehouse q	SM_{xya}	Number of product *a* shipped from facility *x* to facility *y*, $x,y \epsilon \{p,q,i,j,m,n,l,o,s\}$, $x \neq y$
fj_i	Number of jobs created due to establishing distribution i	N_{xyv}	Number of vehicle v from facility *x* to facility *y*, $x,y \epsilon \{p,q,i,j,m,n,l,o,s\}$, $x \neq y$
fj_m	Number of jobs created due to establishing collector m	$y_m = \{0,1\}$	If collector m chosen, it gets value 1 and 0 otherwise
mc_{pa}	Cost of producing a unit of product *a* by producer p	$A_{ja} = \{0,1\}$	If quality of returned product a suitable for repairing, it gets the value of 1 and0 otherwise
pc_{kc}	Purchasing cost of raw material c at supplier k	$B_{ja} = \{0,1\}$	If quality of returned product a suitable for reprocessing, it gets the value of 1 and 0 otherwise
qu_{ja}	Quality of return product *a* from customer j	$C_{ja} = \{0,1\}$	If quality of returned product a suitable for recycling, it gets the value of 1 and0 otherwise
qu_{rep}	Minimum quality required for repairing	$D_{ja} = \{0,1\}$	If quality of returned product a suitable for destruction, it gets the value of 1 and 0 otherwise

1. INTRODUCTION

Collection and reuse of consumed products has become customary [1]. This has increased interest, somehow due to environmental concerns (such as air pollution, waste disposal, and reduction of natural resources), as well as the increase in probable profit obtainable from sustainable products (finding new sources of revenue or reduction of production costs through product repair or recycling). As a result, End-of-Life (EOL) product management is a necessary phase, in supply chain (SC) design [2]. For example, an organization can benefit from cost and resource savings and reputation improvements by solving environmental problems [3]. Maintain profitability while doing business through environmentally and socially sustainable activities, is an optimization challenge for organizations globally for our society [4].

A supply chain in addition to supplier and producer includes retailers, customers, warehouses, distributors and etc [5]. A large amount of waste paper is disposed of in Iran instead of recovered, which had health and environmental damages. Collection, repair and proper disposal of waste paper without harming the environment need to design an efficient closed-loop supply chain (CLSC) network [6]. The closed-loop supply chain is constructed when both the forward and reverse chains are considered [7]. The main challenge in CLSC is designing a network while considering triple principles of sustainability (in supply chain), i.e. economic as well as environmental and social principles [8].

Again, the reverse chain also includes such sections as collection, recycling, repair and disposal centers, in order to minimize wastes of material and products, in the chain [9]. Manufacturers are forced by governmental laws to consider EOL products, and to perform their social responsibility towards the environment [10].

In addition to environmental responsibility, corporate social responsibility (CSR) may affect job creation. In fact, the reverse chain prevents waste of resources, reduces environmental pollutions, leads to gaining profit from secondary goods, creates competition, and increases the efficiency level of the chain. In general, closed loop supply chain may follow economic, competitive, qualitative, environmental, and social conditions, in order to achieve its goal [11].

Classification policy considered in the paper resembles the model presented by Masoudipour et al. [12] Industry dependence is one of the major issues in the models presented in the literature on recycling options. Various options have been provided in each model. The model provided by Masoudipour et al. [12] has had no waste; however, wastes and the need for their disposal are more common. therefore, various recycling options have been considered in this paper to be efficient in different industries including clothing, automotive, and etc.

Transportation is one of the factors that play an important role in logistics and supply chain management [1]. This paper, by designing the vehicle routing and locating facilities problem in a sustainable supply chain, and reject the needs to define the sorting ratios by providing a conditional model (such as Masoudipour et al. [12]) based on the quality of the returned products, helped to solve the problem. The present study seeks to answer the following questions:

- Why organizations and governments in addition to focusing on new products management and planning have to allocate time and financial resources to manage returned products by the customer?
- Considering type of products and conflicting goals, how should routing in closed loop supply chain take place?

Martínez-Salazar et al. [13] focused on the distribution of beverage products in the city. Customers demand will be delivered to consumers after routing homogeneous limited capacity vehicles. Their problem could be considered as a development of two-level routing-locating problems; which will be performed direct transportation in the first level and routing in its second level.

Garg et al. [14] presented a model for determining the flow of products and the optimal number of vehicles needed in the forward chain. Their research concerns development of present chain in an Indian electrical company into CLSC as the company policy towards green production. In present research, in addition to these goals; optimum number of vehicles in reverse chain also will be considered. The decision also affects the network strategy for making optimal decision on the location of returning products.

Maiti and Giri [15] have applied game theory in order to study recycling policies. Their classification policy was based on minimum pre-specified quality which is calculated based on remanufacturing expenses. If returned product would be of higher quality than minimum level required, it would be sent for remanufacturing. Otherwise, it will be sold in secondary market. According to their recycling policies, returned products may be recycled, with or without any proposal for exchange. The idea of testing the effectiveness of exchange proposal with return rate of products [16].

Masoudipour et al. [12] have presented a sample of CLSC in textile industry. After EOL period, these products will be collected. The innovation of this research is due to the new chains in the design of the CLCS, which, in addition to environmental benefits, increases the overall chain profit, and provides a new method for separating return products between different levels in the chain [17].

Sustainable supply chain has become the cornerstone of any company that seeks to achieve sustainable goals [18] and achieving the goals of sustainability is impeded by disconnects between supply chain vision, strategy, and execution [19]. As it is clear by literature, providing an appropriate technique to separate reverse chain products with no need to define initial quantities is of high importance. The paper continues work done by Masoudipour et al. [12] in which they have considered a CLSC modeling problem, based on quality of returned products. They have changed a non-linear problem to a linear one. Later, routing vehicle with specified capacity and locating facilities have been added to the above problem. Also, the multi-purpose multi-product network has been considered with realistic facilities.

2. PROBLEM DEFINITION

CLSC considered in the paper is a multi-level network including suppliers, procedures, customers’ areas, distribution, collection, recycling, and disposal centers, reuse market, and secondary supply chain which combines network design-related decisions in both forward and reverse flows. As shown in Figure 1, in forward chain raw materials will be moved to the factories. Then, final products will be packaged and transferred to warehouses. Considering customers’ requirements, final products will be transferred to distribution centers. Demands are sent to customer zones through distribution centers and vehicles. Returned products primarily will be collected and evaluated in collection centers.

Four recycling options are provided such as repair, reprocess, disposal, and recycling through the sale of products returned to another chain. Minimum required

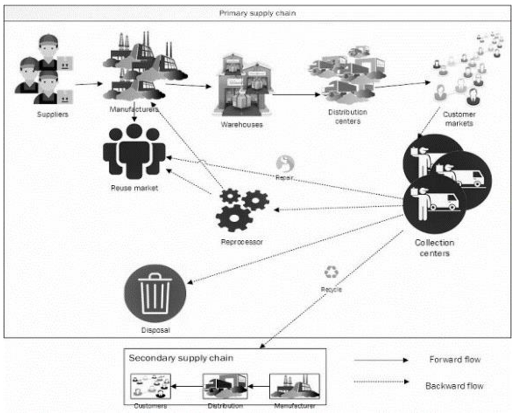

Figure 1. An overview of proposed SCLSC

quality to sort returned products will be defined according to classification policies. Items with higher quality than the minimum required for repair will be sent to reuse markets. Second recycling option has been designed for those returned products with lower quality than minimum required for repair, and higher quality than the minimum required for remanufacturing. These returned products will be sent to reprocessing centers and improved items will be sent to procedures, as reprocessed products and the remaining products will be sent to reuse markets. Third recycling option concerns those returned products with lower quality than the minimum required for remanufacturing, and higher than minimum quality required for recycling. Finally, those returned products with the lowest quality which may not be repaired, remanufactured or recycled will be sent to disposal centers.

As a result, the flow rate between each facility belonging to various levels according to demand, capacity, and cost will be specified. This approach enables us to combine tactical decisions (such as selecting type of vehicles) or material flow decisions with strategic decision-making (such as facility locating) [20].

3. MODELLING

3. 1. Assumptions To model the problem defined in Figure 1, following assumptions are considered:

- Multi-level model of several products have been considered.
- All customers' demands have to be met; and all products returned from demand areas have to be collected and evaluated in collection centers.
- Demand points locations have been fixed. Location and capacity of suppliers, procedures, reuse markets, reprocessor and recycling centers have been pre-determined.
- Each product has been produced of different components; and, components are supplied by various suppliers.
- Method of quality measurement of returned products depends on the nature of related industry.
- Products flow takes place just between two consecutive centers.
- Used products classification policies are calculated from the quality ranges in which they are located [20].

3. 2. Mathematical Model Here, certain model of the problem will be first formulated through a mixed-integer non-linear model. sets, parameters and Decision variables are defined in nomenclature table. Then, mathematical model of sustainable CLSC network problem design has been presented in apendix, considering routing and quality of products.

The model includes three objective functions that is mentioned in Apendix: (A1) minimizing total economic costs; (A2) minimizing total environmental costs; and, (A3) maximizing all the social benefits that conflict with each other. Objective function (A1) reduces total costs including, transportation, operational, fixed construction costs, as well as purchase costs. Objective function (A2) reduces total environmental costs including transportation, manufacturing, establishing, destruction, and reprocessing costs. Objective function (A3) maximizes the whole social benefits such as number of works created against the lost days.

Also constraints are mentioned in apendix. First constraint in Equation (A4) emphasizes that, if a customer is allocated to a distribution facility, will receive all of its demands from the same facility. Constraint (A5) shows that quantity of raw material s flowing from supplier k to manufacturer p, is in balance. Constraint (A6) shows that product a flow from manufacturers to warehouse q is equal to product a flow from warehouse q to distributors. Constraint (A7) computes flow of product manufactured in factory p. Constraint (A8) shows quantity of product transferred to customer j, from distributors. Constraint (A9) shows quantity of product transferred from customer j to collection center m.

Constraint (A10) shows conditional classification policies based on quality of returned goods, through four if-then decision makings. In first equation of constraint (A10), if return quality (qu_{ja}) would be higher than minimum quality required for repair (qu_{rep}), product could be repaired (A_{ja}). If quality of return good would be lower than minimum quality required for repair and higher than minimum quality required for remanufacturing (qu_{rem}), then the product may be remanufactured (B_{ja}). If quality is lower than qu_{rem} but higher than minimum quality required for recycling (qu_{rec}), then product will be sent to other chain for recycling (C_{ja}). Finally, if quality would be lower than qu_{rec}, product will be sent to be disposed (D_{ja}). Linearization method of if-then constraints has been discussed in the literature [16]. Constraints (A11) –

(A22) compute set of repairable, reprocessable, and recyclable products, disposable, respectively.

Constraints (A23) and (A24) ensure that reprocessed items, collected from customers to manufacturers and reuse markets. Constraints (A25) to (A31) are capacity constraints related to each facility. Constraints (A32) to (A41) compute total number of vehicles required to send products, from each facility to the other. Constraint (42) forces raw materials to be supplied only from those suppliers selected. In this constraint, M is a large quantity. Constraints (A43) to (A45) state the point that at least one of each warehouse, distribution, and collection centers has to be constructed, respectively. Constraint (A46) guarantees binary and non-negative nature of decision variables.

3. 3. The Augmented E-Constraint Method

Considering the above model, proposed closed loop supply chain network design (CSCND) is a mixed multiple objective programming problem. Several methods have been developed in papers to confront these models. Augmented Eps-constraint method has been proposed by Mavrotas [21] for multi-objective model. The method tries to implement augmented eps-constraint method for production of desirable Pareto solutions in a multiple objective mathematical program (MOMP). This is a recognized reality that decision makers are mostly not sure how to give proper weight to different objectives; because, they are not interested in stressing on more than one objective.

However, other objectives are ignored by them. Considering the above problems, the method may be considered as an optimum pareto technique which takes all objectives simultaneously into consideration, with no consideration of weight. Augmented Eps-constraint (AUGMECON) method has been first developed and generalized for multiple objective problems. AUGMECON is a new version of ordinary eps-constraint method which provides some solutions for its recognized risks. Defeated solutions produced by it are all effective. Consider a multiple objective mathematical problem:

$$\min\left(f_1(x), f_2(x), \dots, f_p(x)\right) \quad \text{s.t.} \quad x \in s \tag{1}$$

which $\boldsymbol{x}$ is decision variables vector, $f_1(x), f_2(x), \dots, f_p(x)$ are objective functions, and $\boldsymbol{s}$ is justified area.

$$\begin{aligned} &\min\left(f_1(x) + eps \times ({}^{s_2}/{}_{r_2} + \cdots + {}^{s_p}/{}_{r_p}\right) \\ &\text{s.t.} \\ &f_2(x) + s_2 = e_2 \\ &f_p(x) + s_p = e_p \\ &x \in s \, , s_i \in R^+ \end{aligned} \tag{2}$$

where, $\boldsymbol{s_i}$ are auxiliary variables, ***eps*** is a small enough value (usually between 10^{-3} and 10^{-6}), and $\boldsymbol{r_i}$ is changing range of objective function i. Also, $\boldsymbol{e_i}$ will be computed through following equation:

$$\begin{aligned} &e_i = f_i^{worst}(x) + k \times \Delta e_i \\ &x \in s, k = 0,1,2,\dots,n \; and \; \Delta e_i = \frac{f_i^{best}(x) - f_i^{worst}(x)}{n} \end{aligned} \tag{3}$$

Changing right side of constrained objective function (e_i), effective solution will be obtained for the problem. Obtaining of all the solutions, decision could be made based on existing information.

4. COMPUTATIONAL EXPERIMENTS

Here, the model proposed for designing sustainable closed loop supply chain has been tested through numerical testing. Sets have been selected via random assignment experimental method so that it may be assured that all parameters have been solved on configuration; and, they have considerable impact chain. Tests are classified in two groups: mainly focusing on effects of quality of returned goods and return rate on SCLSC model. Table 1 shows size of test problem (number of facilities, capacities and other parameters).

TABLE 1. Parameters of the example

Parameter	Value	Parameter	Value	Parameter	Value
K	3	Capacity of facilities	$\sim U(demand, 3*demand)$	Environmental effects of transportation	$\sim U(100, 500)$
P	2	Capacity of vehicles	[200,250,300]	Environmental effects of operation	$\sim U(100, 200)$
Q	1	demand	$\sim U(1, 40)$ for product 1 , $\sim U(1, 100)$ for product 2	qu_{rep}	[85,99]
I	2	qu_{ja}	$\sim U(1, 100)$	qu_{rem}	[55,85]
J	3	cp_v	[500,700,800]	qu_{rec}	[25,55]
M	2	Transportation cost	Distance between facilities×1	pc_{kc}	$\sim U(1, 20)$
N	1	vol_a	[1,2]	mc_{pa}	$\sim U(5, 20)$
L	1	vol_c	[0.25,0.15,0.20,0.35]	Fj	$\sim U(40, 150)$
O	1	C_{ac}	[[1,1,1,1][2,3,3,1]]	fc_p	$\sim U(1, 5)$
S	1	Job created	$\sim U(40, 150)$	Fc	$\sim U(100, 300)$
V	3	Lost days	$\sim U(0, 30)$	C	4
A	2	Operational cost	$\sim U(5,50)$		

In order to validate and verify the integrity of the model, the problem has been solved with AUGMECON method in IBM CPLEX 12.6 For small-size and the meta-heuristic non-dominated sorting algorithm (NSGA II) in MATLAB 9.4 for medium and large-sized instances. Optimization software used may use non-linear if-then constraint, in case of similarity with following instruction. Alternately, linear version of problem also may be used.

$if\ (condition\ is\ met)$
{response1;}
else
{response2;} (4)

4. 1. Test on Return Rate

Here, effect of return rate of products on values of objective function has been analyzed. Solutions obtained for various return rates in small-size have been shown in Table 2. Also, environmental and economic costs in addition to social benefits have been shown in Figure 2. Using the results from Table 2 and Figure 2, effects of diversity of return rates on objective functions may be analyzed, as mentioned below. Through increase of return rate, social advantages also will be increased, in addition to increase made in economic and environmental costs. The more return rate increases, the more people would be employed by facilities; and, more vehicles will be used. This way, on return rate of 0.9, even second collection facility will be constructed.

Through increase of vehicles and returned products, environmental transportation costs and vehicles rental costs will be also increased. Through increase of return rate, number of products in need of repair, remanufacturing, recycling and/or disposal will be also increased. Operational costs of facilities related to reverse flow also will be increased. As a result, total economic and environmental costs will be on an uptrend. On return rate of 0.9, considerable increase would be made in economic and environmental costs; the reason of which is construction of second collection facility. Percentage relative error (PRE) is used to measure performance of instances.

$$PRE_i = \left|Alg_{sol}^i - O^i\right| / O^i \tag{5}$$

where Alg_{sol}^i is the objective i which obtained by selected algorithm and O^i is the optimum objective i obtained by CPLEX. Table 3 shows the computational results for small, medium large size problems. Analysis of variance (ANOVA) is performed, Due to the nature of meta-heuristics (NSGA II). As shown in Table 4, the ANOVA output for obtained PRE of both algorithms were not significant because the p-value was approximately 0.05. Although our focus has been on modeling the problem, solving methods have been validated.

4. 2. Test on Quality of Returns

In this section, effect of returned products' quality on objective functions has been studied. First, customers have been classified based on return rate of products, in reverse chain. Customers group A is among those with return rate of about 0.2 (between 0.1 and 0.3). Customers group B is among those with return rate of 0.4 to 0.6. Customers group C has highest return rate (0.7 to 0.9).

These tests are performed in four systematic groups. Groups 1 to 3 are focused on customers' behavior in groups A, B, and C of customers. The last group studies mutual effects of all customers on objective functions. In the first test group, return products are only collected from customers group A. Average quality of returned products for the test is {5, 10, 15, …, and 95}. Other values of parameters are the same as previous section. Return rate of products in this test is between 0.1- 0.3. Centers used in reverse flow will also change, through change of returned products' quality. When quality is low, from 5 to 15 products will be disposed; not being sent to other facilities. Through increase in quality, other centers are active but not used. As it is clear in Figure 3, within quality range of 25 to 45, lowest values of economic and environmental objective functions are observed. Social objective function is almost similar within various ranges; while, it changes a little. Second test group focuses on returned products collected from customers group B, with average quality of {5, 10, 15, …, and 95}. Against each value of different quality, a test has been performed. The results have been presented in Figure 4. As observed in the figure, test results resemble those of test performed on Customers group A. Within quality range of 55 to 80, there are highest values of environmental, economic, and social objective functions. The highest level concerns social objective function; however, other functions are in their worst positions.

Also, within the quality range of 25 to 45, lowest economic objective function has been observed; and, within the quality range of 90 to 95, best value of environmental function has been observed. In general, best values of objective functions have been observed,

TABLE 2. Solutions

Variables	$\alpha = 0.1$	$\alpha = 0.2$	$\alpha = 0.3$	$\alpha = 0.4$	$\alpha = 0.5$	$\alpha = 0.6$	$\alpha = 0.7$	$\alpha = 0.8$	$\alpha = 0.9$
z1	119638	122295	124379	126734	131280	134776	136985	139167	186825
z2	63149	64300	64831	65619	68125	70921	71493	72162	96678
z3	600.708	609.065	616.705	624.062	640.418	644.152	651.33	658.507	739.944

within the range of 25 to 45. The third test group also has been designed for customers group C with highest return rate (0.7-0.9). Quality range also has been {5, 10, …, and 95}. It is clear from Figure 5 that, within the quality range of 20 lowest values of economic and within the quality range of 90 to 95, best value of environmental function has been observed.

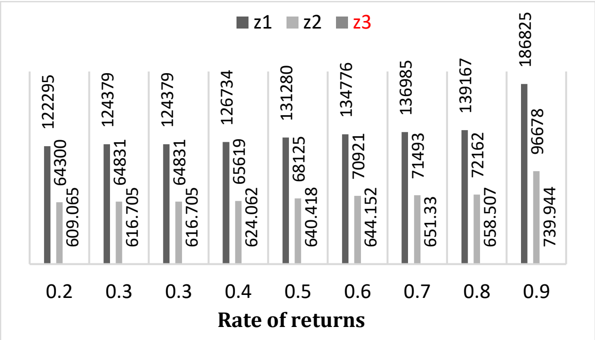

Figure 2. Objective functions versus rate of returns

TABLE 3. Computational results for problems

Problem (K,P,Q,I,J,M,A, C,V)	Size	AGUMECON	PRE_i	NSGA II	PRE_i
		128511	0.0031	128909	0.003
3-2-1-2-3-2-2-4-3	S	63606	0.028	63423	0.025
		557.459	0.059	556.898	0.060
		513070	0.031	497701	0.0001
4,3,1,3,5,3,3,4,4,3	M	259551	0.0002	259544	0.0002
		881.785	0.0183	892.289	0.0066
		n.s.	n.s.	919033	0.0409
10,6,2,5,10,5,3,4,4,3	L	n.s.	n.s.	461153	0.0009
		n.s.	n.s.	984.087	0.3127

TABLE 4. ANOVA results

	ANOVA of PRE			
	Sum of Squares	df	Mean square	F
Between groups	0.000144	1	0.000144	0.28
Within groups	0.005231	10	0.000523	
Total	0.005375	11		

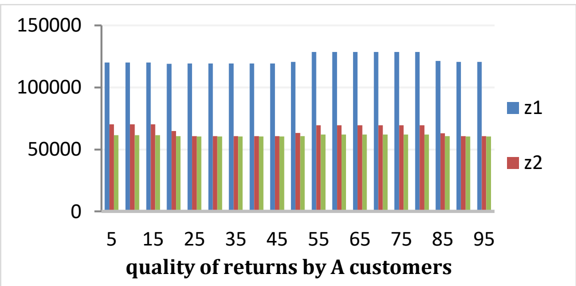

Figure 3. Objective functions versus quality of returns by A customers

Also, within the quality range of 55 to 80, best value of social function has been observed. Furthermore, like pervious tests, best value of objective functions within the quality range of 25 to 45 has been obtained. The fourth test group has been designed for all customers. Rate of return in this test is between 0.1 and 0.9. The test results (Figure 6) are the same as those for test performed on customers group B.

5. CONCLUSION AND FUTURE RESEARCHES

In this article, there has been delivered the mathematical model to design the network of sustainable supply chain. The aim of this model study is to minimize the economic and environmental costs and to maximize the social costs of the facilities with different products and the facilities with different capacities by considering the

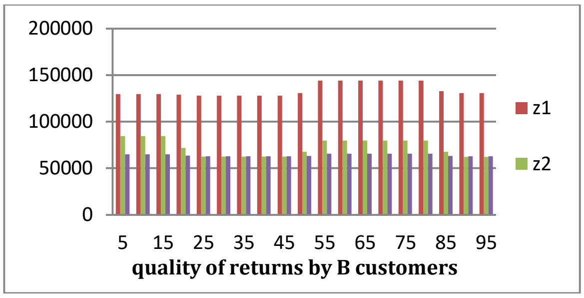

Figure 4. Objective functions versus quality of returns by B customers

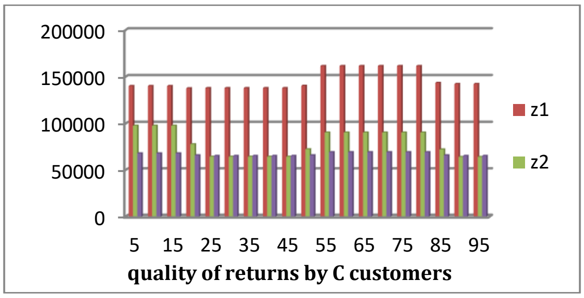

Figure 5. Objective functions versus quality of returns by C customers

Figure 6. Objective functions versus quality of returns by all customers

transportation of the products with different vehicles. The model is solved by AUGMECON method with CPLEX and then one Meta heuristic algorithm (NSGA II) is used. The ANOVA test have showed that meta-heuristics provided efficient results with a confidence level of 95%. Sensitivity analysis under tests performed in section 4 includes following results:

- Supply chain becoming closed would be resulted in creation of new jobs and higher costs, in addition to higher revenues. Moreover, the need for raw material will be reduced. When returned products are sent to reuse markets and secondary chain, sales of products increases.
- If incentive policies are used for purchase of products from customers; they have to satisfy those customers who return average quality products. The reason is that, there are less economic and social costs involved.

In future decisions, environmental objective function has to be more considered, besides other functions; because, currently environmental issues are integral part of all industries. Moreover, main objective of closed loop supply chain is maintaining environmental sustainability.

Through the model provided in the paper, possibility of closing chain in industry with no primary information at hand regarding classification will be studied, in addition to the effects of such an action on economic and environmental costs, as well as social advantages. Defining quality in various industries is considered as an innovative point of the model; while, the model includes vehicles routing in supply chain, adding reuse and secondary markets, as well as model's flexibility.

Also, the paper analyzes sensitivity through a numerical example in which four recycling options have been taken into consideration: repair, remanufacturing, recycling in secondary market, and disposal.

Managerial insights from the proposed model can be summarized as:

- Considering sustainability in the supply chain leads to more attention to the environmental and social benefits derived from the chain and brings the model closer to the real world.
- Merging supply chain network design and routing-locating problem, leads to strategic and operational decisions.
- Product returns are classified according to quality, which gives flexibility to the model.
- According to the analysis, it is clear that the products with qualitative range of 25 to 45 have the best value of functions and must focus on this range of returned products.

The results obtained from solving the model shows that those products with quality of 25 to 45 have better total values for social, economic, and environmental objective functions in the chain; and, they create business opportunities.

Therefore, incentive suggestions to customers to return such products have to be ideal so that return rate of products with average quality would be increased. In general, the model may be used by most of industries. One of restrictions of the research is the point that inventory control has not been taken into consideration. Also, current model has been designed for one period of time; however, it could be developed to study numerous products in several time periods. Moreover, as for the future studies, the model may be developed through using inventory management in manufacturing companies, possibility of missed sales, and creation of cross docking facility to increase social, environmental and economic sustainability of the system.

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7. APENDIX

Objective function and constraints

$$\begin{aligned}\min\ f_1 = {} & \sum_p fc_p + \sum_i fc_i y_i + \sum_q fc_q y_q + \sum_m f_m y_m + \sum_k \sum_p \sum_c SM_{kp} pc_{kc} \sigma_k + \sum_p \sum_a mc_{pa} H_{pa} + \\ & \sum_p \sum_q \sum_a SM_{pqa} vc_{qa} + \sum_q \sum_i \sum_a SM_{qia} vc_{ia} + \sum_m \sum_n \sum_a SM_{mna} vc_{na} + \sum_m \sum_l \sum_a SM_{mla} vc_{la} + \sum_k \sum_p \sum_v N_{kpv} c_{kpv} + \\ & \sum_p \sum_q \sum_v N_{pqv} c_{pqv} + \sum_q \sum_i \sum_v N_{qiv} c_{qiv} + \sum_i \sum_j \sum_v N_{ijv} c_{ijv} + \sum_m \sum_n \sum_v N_{mnv} c_{mnv} + \sum_m \sum_l \sum_v N_{mlv} c_{mlv} + \\ & \sum_n \sum_p \sum_v N_{npv} c_{npv} + \sum_v c_v \left(N_{mlv} + N_{npv} + N_{mnv} + N_{ijv} + N_{qiv} + N_{pqv} + N_{kpv} \right)\end{aligned} \tag{A1}$$

$$\begin{aligned}\min\ f_2 = {} & \sum_i eo_i y_i + \sum_q eo_q y_q + \sum_m eo_m y_m + \sum_p \sum_a eo_{pa} H_{pa} + \sum_m \sum_l eo_l SM_{mla} + \\ & \sum_m \sum_n eo_n SM_{mna} + \sum_k \sum_p \sum_v et_{kpv} N_{kpv} + \sum_p \sum_q \sum_v et_{pqv} N_{pqv} + \sum_q \sum_i \sum_v et_{qiv} N_{qiv} + \\ & \sum_i \sum_j \sum_v et_{ijv} N_{ijv} + \sum_m \sum_n \sum_v et_{mnv} N_{mnv} + \sum_m \sum_l \sum_v et_{mlv} N_{mlv} + \sum_n \sum_p \sum_v et_{npv} N_{npv}\end{aligned} \tag{A2}$$

$$\begin{aligned}\max\ f_3 = {} & \begin{bmatrix} \sum_i y_i fj_i + \sum_q y_q fj_q + \sum_m y_m fj_m + \sum_p \sum_a H_{pa} vj_{pa} / cap_{pa} + \\ \sum_p \sum_q \sum_a SM_{pqa} vj_q / cap_{qa} + \sum_q \sum_i \sum_a SM_{qia} vj_i / cap_{ia} + \sum_j \sum_m \sum_a SM_{lma} vj_m / cap_{ma} + \\ \sum_m \sum_n \sum_a SM_{mna} vj_n / cap_{na} + \sum_m \sum_l \sum_a SM_{mla} vj_l / cap_{la} \end{bmatrix} + \sum_k \sum_p \sum_v N_{kpv} + \sum_p \sum_q \sum_v N_{pqv} + \\ & \sum_q \sum_i \sum_v N_{qiv} + \sum_i \sum_j \sum_v N_{ijv} + \sum_m \sum_n \sum_v N_{mnv} + \sum_m \sum_l \sum_v N_{mlv} + \sum_m \sum_o \sum_v N_{mov} + \sum_m \sum_s \sum_v N_{msv} + \sum_n \sum_p \sum_v N_{npv} + \sum_n \sum_o \sum_v N_{nov} - \\ & \begin{bmatrix} \sum_p \sum_a H_{pa} vl_{pa} / cap_{pa} + \sum_p \sum_q \sum_a SM_{pqa} vl_q / cap_{qa} + \sum_q \sum_i \sum_a SM_{qia} vl_i / cap_{ia} + \\ \sum_j \sum_m \sum_a SM_{lma} vl_m / cap_{ma} + \sum_m \sum_n \sum_a SM_{mna} vl_n / cap_{na} + \sum_m \sum_l \sum_a SM_{mla} vl_l / cap_{la} \end{bmatrix}\end{aligned} \tag{A3}$$

Subject to

$$\sum_q SM_{qia} = \sum_j y_j d_{ja} \qquad \forall a \in A, \forall i \in I \tag{A4}$$

$$\sum_k SM_{kpc} = \sum_q \sum_a c_{ac} SM_{pqa} \qquad \forall p \in P, \forall c \in C \tag{A5}$$

$$\sum_p SM_{pqa} = \sum_i SM_{qia} \qquad \forall q \in Q, \forall a \in A \tag{A6}$$

$$\sum_q SM_{pqa} = H_{pa} \qquad \forall p \in P, \forall a \in A \tag{A7}$$

$$\sum_i SM_{ija} = d_{ja} \qquad \forall j \in J, \forall a \in A \tag{A8}$$

$$\sum_m SM_{jma} = d_{ja}\alpha_{ja} \qquad \forall j \in J, \forall a \in A \tag{A9}$$

$$\begin{cases} if\left(qu_{ja} \geq qu_{rep}\right) \Rightarrow A_{ja}=1 \\ if\left(qu_{rem} \leq qu_{ja} < qu_{rep}\right) \Rightarrow B_{ja}=1 \\ if\left(qu_{rec} \leq qu_{ja} < qu_{rem}\right) \Rightarrow C_{ja}=1 \\ if\left(qu_{ja} < qu_{rec}\right) \Rightarrow D_{ja}=1 \end{cases} \qquad \forall j \in J, \forall a \in A \tag{A10}$$

$$RA_{ja} = d_{ja}\alpha_{ja}A_{ja} \qquad \forall j \in J, \forall a \in A \tag{A11}$$

$$RB_{ja} = d_{ja}\alpha_{ja}B_{ja} \qquad \forall j \in J, \forall a \in A \tag{A12}$$

$$RC_{ja} = d_{ja}\alpha_{ja}C_{ja} \qquad \forall j \in J, \forall a \in A \tag{A13}$$

$$RD_{ja} = d_{ja}\alpha_{ja}D_{ja} \qquad \forall j \in J, \forall a \in A \tag{A14}$$

$$y_m RA_{ja} \leq QA_{jma} \qquad \forall j \in J, \forall a \in A, \forall m \in M \tag{A15}$$

$$y_m RB_{ja} \leq QB_{jma} \qquad \forall j \in J, \forall a \in A, \forall m \in M \tag{A16}$$

$$y_m RC_{ja} \leq QC_{jma} \qquad \forall j \in J, \forall a \in A, \forall m \in M \tag{A17}$$

$$y_m RD_{ja} \leq QD_{jma} \qquad \forall j \in J, \forall a \in A, \forall m \in M \tag{A18}$$

$$\sum_j QA_{jma} = \sum_o SM_{moa} \qquad \forall a \in A, \forall m \in M \tag{A19}$$

$$\sum_j QB_{jma} = \sum_n SM_{mna} \qquad \forall a \in A, \forall m \in M \tag{A20}$$

$$\sum_j QC_{jma} = \sum_s SM_{msa} \qquad \forall a \in A, \forall m \in M \tag{A21}$$

$$\sum_j QD_{jma} = \sum_l SM_{mla} \qquad \forall a \in A, \forall m \in M \tag{A22}$$

$$\sum_m \gamma_n SM_{mna} = \sum_p SM_{npa} \qquad \forall a \in A, \forall n \in N \tag{A23}$$

$$\sum_m \left(1-\gamma_n\right) SM_{mna} = \sum_o SM_{noa} \qquad \forall a \in A, \forall n \in N \tag{A24}$$

$$\sum_c \sum_p SM_{kpc} vol_c \leq cap_k \qquad \forall k \in K \tag{A25}$$

$$\sum_a \sum_q SM_{pqa} vol_a \leq cap_p \qquad \forall p \in P \tag{A26}$$

$$\sum_a \sum_i SM_{qia} vol_a \leq cap_q y_q \qquad \forall q \in Q \tag{A27}$$

$$\sum_a \sum_j SM_{ija} vol_a \leq cap_i y_i \qquad \forall i \in I \tag{A28}$$

$$\sum_a \sum_j SM_{jma} vol_a \leq cap_m y_m \qquad \forall m \in M \tag{A29}$$

$$\sum_a \sum_m SM_{mna} vol_a \leq cap_n \qquad \forall n \in N \tag{A30}$$

$$\sum_a \sum_m SM_{mla} vol_a \leq cap_l \qquad \forall l \in L \tag{A31}$$

$$\sum_c SM_{kpc} vol_c \leq \sum_v cap_v N_{kpv} \qquad \forall k \in K, \forall p \in P \tag{A32}$$

$$\sum_a SM_{pqa} vol_a \leq \sum_v cap_v N_{pqv} \qquad \forall p \in P, \forall q \in Q \tag{A33}$$

$$\sum_a SM_{qia} vol_a \leq \sum_v cap_v N_{qiv} \qquad \forall q \in Q, \forall i \in I \tag{A34}$$

$$\sum_a SM_{ija} vol_a \le \sum_v cap_v N_{ijv} \qquad \forall i \in I, \forall j \in J \tag{A35}$$

$$\sum_a SM_{mna} vol_a \le \sum_v cap_v N_{mnv} \qquad \forall m \in M, \forall n \in N \tag{A36}$$

$$\sum_a SM_{mla} vol_a \le \sum_v cap_v N_{mlv} \qquad \forall m \in M, \forall l \in L \tag{A37}$$

$$\sum_a SM_{npa} vol_a \le \sum_v cap_v N_{npv} \qquad \forall n \in N, \forall p \in P \tag{A38}$$

$$\sum_a SM_{noa} vol_a \le \sum_v cap_v N_{nov} \qquad \forall n \in N, \forall o \in O \tag{A39}$$

$$\sum_a SM_{moa} vol_a \le \sum_v cap_v N_{mov} \qquad \forall m \in M, \forall o \in O \tag{A40}$$

$$\sum_a SM_{msa} vol_a \le \sum_v cap_v N_{msv} \qquad \forall m \in M, \forall s \in S \tag{A41}$$

$$\sum_p \sum_c SM_{kpc} \le \sigma_k M \qquad \forall k \in K \tag{A42}$$

$$\sum_q y_q \ge 1 \tag{A43}$$

$$\sum_i y_i \ge 1 \tag{A44}$$

$$\sum_m y_m \ge 1 \tag{A45}$$

$$\begin{aligned} &\sigma_k, y_i, y_m, y_q, A_{ja}, B_{ja}, C_{ja}, D_{ja} = \{0,1\} \\ &SM_{kpc}, SM_{pqa}, SM_{qia}, SM_{ija}, SM_{jma}, SM_{moa}, SM_{mna}, SM_{mla}, SM_{msa}, SM_{npa}, SM_{noa} \ge 0 \\ &N_{kpv}, N_{pqv}, N_{qiv}, N_{ijv}, N_{mnv}, N_{mlv}, N_{mov}, N_{msv}, N_{npv}, N_{nov} \ge 0 \\ &H_{pa}, RA_{ja}, RB_{ja}, RC_{ja}, RD_{ja}, QA_{jma}, QB_{jma}, QC_{jma}, QD_{jma} \ge 0 \end{aligned} \qquad \begin{aligned} &\forall k \in K, \forall i \in I, \forall q \in Q, \forall m \in M, \\ &\forall j \in J, \forall a \in A, \forall n \in N, \forall o \in O, \\ &\forall p \in P, \forall l \in L, \forall c \in C, \forall s \in S \end{aligned} \tag{A46}$$

A Novel Sustainable Closed-loop Supply Chain Network Design by Considering Routing and Quality of Products

S. H. Mirmohammadi, R. Sahraeian

College of Engineering, Department of Industrial Engineering, Shahed University, Tehran, Iran

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چکیده

یکی از تصمیمات استراتژیک در زنجیره‌تأمین، طراحی شبکه زنجیره‌تأمین است، که تأثیر فراوانی بر هزینه‌ها و همچنین سطح رضایت مندی مشتریان دارد. این مقاله به طراحی شبکه توزیعی شامل تعیین تعداد و موقعیت تسهیلات، چگونگی تخصیص مشتریان در شبکه و تعیین میزان حمل‌کالاهای مختلف از مبادی گوناگون به مقاصد متفاوت در شبکه توزیع؛ به گونه‌ای که تقاضای تمامی مشتریان با کمترین هزینه و با توجه به محدودیت‌های موجود، برآورده گردد؛ می‌پردازد. علاوه بر زنجیره ثانویه و بازار استفاده مجدد به عنوان گزینه بازیابی، انعطاف مدل در تعریف کیفیت و مسیریابی-مکان‌یابی نیز در میان نقاط نوآوری مدل است. اولاً، مدل در زنجیره مستقیم شامل تأمین‌کننده، تولیدکننده، انبار، توزیع‌کننده و مشتری است و در زنجیره برگشت نیز شامل بازار استفاده مجدد، زنجیره تأمین ثانویه، مراکز جمع‌آوری، بازفرآوری و انهدام است. این مدل برای صنایع با انواع استراتژی‌ها قابل تعمیم است. دوماً، یک تحلیل حساسیت بر روی مثالی عددی انجام شده‌است؛ همچنین روش متاهیوریستیک ژنتیک۲ برای مثال عددی بزرگ‌تر بکار گرفته شده‌است، که با آزمون ANOVA کارایی آن سنجیده شد. نتایج نشان می‌دهد که محصولات برگشتی با کیفیت متوسط منجر به هزینه‌های کمتر و مزایای اجتماعی بیشتر می‌گردد و روش متاهیوریستیک NSGA II کارا است. چرا که در کنار ایجاد فرصت‌های کسب و کار، هزینه‌های اقتصادی و زیست محیطی کمتری را متحمل می‌شود.

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