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A Novel Supply Chain Network Design Considering Customer Segmentation using Lagrangian Relaxation Algorithm

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Abstract

Environmental issues are unavoidable in supply chain management. Providing different level of green products is a major subject in this area for distinctive customer segments. In this research, a capacitated network design problem with different levels of green products for their specific demands is considered. This network has different levels with multiple products. The forward/reverse network consists of plants, hybrid warehouse/disposal centers, and customers. Two types of vehicles are considered to transport the products among the network. Each customer segment has specific needs based on their attitude to the greenness subject and their willingness to pay more money in order to attain a product with higher degree of greenness. A quadratic function is assumed for extra money to produce green products. To evaluate the reliability of the model, a real example proposed. Large size sample problems are solved using an efficient Lagrangian relaxation method. The results presents that the proposed method solved large size sample problems in a reasonable time.

***Keywords**:* Level of Greenness, Lagrangian Relaxation, Supply chain Design, Custoer Segmentation

1.Introduction

In today's industrialized societies, the environment is damaged strictly (Biswas & Roy, 2015). Environmental disasters are made by changing in water, air and climate which results to admit the green economy. Many researchs includes green supply chain management recently (El Saadany & Jaber, 2010; Chekima et al., 2016). In many countries, the subsidy is provided to progress consumers' attitudes toward green products. For example, a tax credit of around 3000$ per plug-in hybrid electric vehicle is provided for by the American Recovery and Reinvestment Act of 2009 (Peng & Peng, 2013; Peterson & Michalek, 2013). To attain an advantage for all supply chains, environmental harms are introduced (Govindan et al., 2014).

One of the major goals in many industries is implementing forward/reverse logistics network because of the ecological footprint, customer satisfaction and reducing costs (Dondo & Méndez, 2016). Therefore, an efficient integrated network helps companies to gain high performance in market.

The configuration of the logistics network is one of the most important issues in supply chain design which includes the determination of the numbers, locations, capacities of facilities and the flow of products between them (Amiri, 2006).

Integrated forward and reverse logistics is a concept that has increasingly gained paramountcy in both industrial and academic areas over the last 20 years. Economic and environmental concerns, incrementing environmental vigilance of people, governmental legislations, and growing competitive pressure which are a number of ineluctably foreordained reasons have caused to the development of multiple models and solutions for integrated forward and reverse logistics (Jayaraman & Yadong Luo, 2007; Kumar & Putnam, 2008; Srivastava & Srivastava, 2006).

According to the literature which is discussed in the next section, there are papers evaluated the green supply chain based on the transportation conditions and polluted gas emission as important green factors. However, the degree of greenness for products based on the customer segmentation's demands as a mathematical model has less attracted the attention of researchers.

In real conditions, a supply chain deals with different customer demands. Each customer segment has specific needs based on their attitude to the greenness subject and their willingness to pay more money in order to attain a product with higher degree of greenness. Hence, taking into account these issues as a mathematical model which considers the customer's segmentations with their demands and trading it off with related costs is highly necessary. In this paper, a multi echelon, multi products and capacitated network design problem with different levels of product greenness is considered. The forward/reverse network consists of plants, hybrid warehouse/disposal centers, and customers. Two types of

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vehicles, small and big; are considered for transportation the products among the network. The problem is solved on a real example to evaluate the reliability of the model. Large size sample problems are solved using an efficient Lagrangian relaxation method.

The rest of the paper is structured as follows. Section 2 reviews some related papers. Section 3 defines the problem and model formulation. In Section 4 a real example is evaluated. The solution approach is proposed in Section 5. Computational results are provided in Section 6. Managerial perspectives and sensitivity analysis are presented in Section 7. Finally, concluding remarks and future researches are discussed in Section 8.

2-Literature Review

A variety of models including perpetual location, network location, and discrete location models have so far been developed predicated on the characteristics and circumscriptions that are commonly considered to be involved in facilities location and distribution network design problems. Facility and demand allocation problems have extensively studied by many researchers.

The uncapacitated facility location problem (UFLP) is the simplest model for distribution network design. determination the locations of facilities such that the cost of the distribution system is minimized is the objective of this model (Farahani et al., 2014; Kratica et al., 2013; Mohammad Nezhad et al., 2013). Once the capacity limitation is introduced, the uncapacitated facility location model (UFLP) is converted to a capacitated facility location model (Fernandes et al., 2014; Guastaroba & Speranza, 2014; Mirmajlesi & Shafaei, 2016; Rahmani & MirHassani, 2014; Toro et al., 2017; Yousefi-Babadi et al., 2021; Brahami et al., 2022; Roosta et al., 2023).

Jayaraman, 1998 studied the capacitated warehouse location problem to satisfy customer demands for different products which involves locating a given number of warehouses. Pirkul & Jayaraman, 1998 elongated the previous problem by locating a given number of plants. They formulated the problem as a mixed integer model and developed a Lagrangian based heuristic solution procedure. Tragantalerngsak et al. (2000) considered a two-echelon facility location problem. determination the number and locations of facilities in both echelons is the goal in order to satisfy customer demand of the product. In order to solve the problem They developed a Lagrangian relaxation based branch and bound algorithm.

In recent years, however, location-allocation models with capacity decisions due to their ability to represent problems more authentically have received more attention . In order to determine the location and capacity level of multi-commodity warehouses to open Askin, Baffo, & Xia (2014) developed a mathematical model. and the suitable distribution route from each manufacturer to each retailer, and the quantity of products stocked at each warehouse and retailer are considered Ko & Evans (2007) to design a dynamic integrated forward/reverse logistics network presented a mixed integer nonlinear programming (MINLP) model and developed a genetic algorithm-based heuristic. Pati et al. (2008) to design a multi-product paper recycling logistics network considered a mixed integer goal programming (MIGP) model. The model investigates the inter-relationship between triple objectives of a recycled paper distribution network. The objectives are the reverse logistics cost minimization , product quality improvement , and environmental benefits maximization through wastepaper increased recovery .

Effect of consumer environmental vigilance (CEA) on incrementing authoritative ordinance of green products is another research stream, which is cognate to the current work. With the elevate of CEA, it is expected to increment congeniality of consuming a product for which an environment-amicable substitute is available (Conrad, 2005). By the incrementation of public cognizance about environmental issues, the market purchase deportment is transmuted; peoples prefer to buy green product in lieu of customary ones but do not pay an inordinate amount of mazuma.Green advertising is one of the best-kenned methods to increment CEA and transmute the people living style to a green life (Haytko & Matulich, 2008). Xia & He, (2014) analyzed a two-echelon supply chain with deterministic product demand, and it has been shown that sharing the carbon emission reduction costs is an effective encouragement for the manufacturer to reduce its carbon emission. to initiate the manufacturer to increase the greening level of product, Ghosh & Shah, (2015) proposed a cost-sharing contract but the proposed mechanism was not capable of reaching the centralized model. Zhang et al. (2015) applied a return policy in a two-stage SC where the demand is a function of price and green quality with two substitutable products (traditional and green product). In their model, CEA is assumed to be a variable as the coefficient of green quality.

Different structures of green supply chains consisting of a manufacturer and a retailer are compared by Ghosh & Shah, 2012 . Results showed that green innovation could be maximized when the manufacturer and the retailer were integrated as a whole system. Droste et al., 2016 by encouraging green investment analyze institutional conditions facilitating the transition towards a green economy. De Giovanni, Reddy, & Zaccour, 2016 to coordinate the recovery efforts investigate the incentive strategies in a closed-loop supply chain. the close loop supply chain network design problems under different assumptions such as different return quality levels and customers' return willingness are investigated by Jeihoonian, Kazemi Zanjani, & Gendreau, 2016.

In regard to greenness, as public awareness increases with regard to environmental issues, consumer buying behavior has shifted toward green products. However, customer attitudes can be influenced by the price and quality of refurbished products (Tsao et al., 2019; Agi et al., 2020; Yilmaz et al., 2022). Coskun et al. (2016) conducted customer segmentation to demonstrate that consumer buying behavior is highly dependent on the price of green products.

According to the literature, there are papers evaluated the green supply chain based on the transportation conditions and polluted gas emission as important green factors. However, the degree of greenness for products based on the customer segmentation's demands as a mathematical model has less attracted the attention of researchers.

Hence, taking into account the level of greenness for products as a mathematical model which considers the customer's segmentations with their specific demands and trading it off with related costs is highly necessary. In general, the review of the researches on supply chain network design reveals that the gap recommended to be studied includes a multi echelon, capacitated and multi product integrated network considering different levels of vehicles and product greenness for specific customer segments with details explained in Section 3.

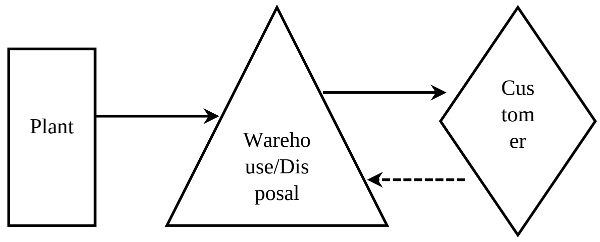
3-Problem Definition and Model Formulation

In this problem, a multi echelon, multi products and capacitated network design problem with different levels of product greenness is considered. The forward/reverse network consists of plants, hybrid warehouse/disposal centers and customers. Two types of vehicles; small and big, are considered to transport the products among the network. Each customer has a rate of return of products. The returned products are transported to disposal centers in a reverse flow.

In real conditions, a supply chain deals with different customer demands. Each customer segment has specific needs based on their attitude to the greenness subject and their willingness to pay more money in order to attain a product with higher degree of greenness. Hence, taking into account these issues as a mathematical model which considers the customer's segmentations with their demands and trading it off with related costs is highly necessary.

the manufacturer must invest some extra money to achieve the green innovation based on the original production process To engender green products,. It is assumed that the plant has different production lines for producing products with different levels of greenness. The production costs of different levels of greenness are not equal to each other. This cost is assumed to be a quadratic function of the green degree (Ghosh & Shah, 2012; Swami & Shah, 2013). As a result, the extra cost for the manufacturer to produce the green products is $C(\theta)=\eta\theta^2/2$, where η is the cost coefficient of the green degree per unit. The schematic model of the problem is illustrated in Figure 1.

Fig1. Schematic model of the problem



The following assumptions are considered in the problem:

- The demand of customers is supplied through multiple sourcing of all warehouses.
- The products have different levels of greenness degree which results to different production and disposal costs.
- The model is assumed as a single period.
- Plants and disposal/warehouse centers have limited capacity.
- Small and big vehicles have different limited capacity and rental costs.
- Potential locations for plants and warehouse/disposal centers have fixed opening cost.

The following notation is used in the formulation of the model.

Indices

N: index set of customer zone i

M: index set of potential warehouse/disposal center j

L: index set of potential plant site k

θ: index set of level of greenness δ

Parameters

b_j: capacity of the potential warehouse/disposal centers at site j

e_k : capacity of the potential plant at site

$\alpha 1$:capacity of small vehicle

$\alpha 2$: capacity of big vehicle

F_j : fixed cost for opening warehouse/disposal centers at site j

G_k : fixed cost for opening plant at site k

$\bar{C}_{jk}$: transportation cost of one unit of demand from plant at site k to warehouse center at site j

C_{ij} : transportation cost of one unit of demand from warehouse/disposal at site j to customer zone i and vice versa

$P_{j\delta}$: disposal cost of one unit of returned product with level of greenness δ to warehouse/disposal centers at site j

η_k : cost coefficient of the green degree per unit at plant at site k

$\beta 1$: cost of hiring one small vehicle

$\beta 2$: cost of hiring one big vehicle

$a_{i\delta}$:demand of customer zone i for product with level of greenness δ

$d_{i\delta}$: rate of return of customer zone i for products with level of greenness δ

Decision variables

$Q1_{kj}$: number of big vehicle rented between plant at site k and warehouse/disposal center at site j

$Q2_{ji}$: number of big vehicle rented between warehouse/disposal center at site j and customer zone i

$Q3_{ij}$: number of big vehicle rented in the reverse flow between customer zone i and warehouse/disposal center at site j

$S1_{kj}$: number of small vehicle rented between plant at site k and warehouse/disposal center at site j

$S2_{ji}$: number of small vehicle rented between warehouse/disposal center at site j and customer zone i

$S3_{ij}$: number of small vehicle rented in the reverse flow between customer zone i and warehouse/disposal center at site j

$X_{ij\delta}$:fraction (regarding $a_{i\delta}$) of demand of customer zone i at green degree of δ delivered from warehouse/disposal centers at site j

$Y_{jk\delta}$: fraction (regarding b_j) of shipment at green degree of δ from plant at site k to warehouse/disposal centers at site j

$$U_j : \begin{cases} 1 \text{ if a warehouse is located at site j} \\ 0 \text{ otherwise} \end{cases}$$

$$V_k : \begin{cases} 1 \text{ if a plant is located at site k} \\ 0 \text{ otherwise} \end{cases}$$

In terms of the above notation, the problem can be formulated as follows.

$$\begin{aligned} Z = Min\sum_{i\in N}\sum_{j\in M}\sum_{\delta\in\theta} C_{ij}a_{i\delta}X_{ij\delta} + \sum_{j\in M}\sum_{k\in L}\sum_{\delta\in\theta}\bar{C}_{jk}b_jY_{jk\delta} + \sum_{j\in M}\sum_{k\in L}\sum_{\delta\in\theta}\left(\frac{\eta_k}{2}\delta^2\right)b_jY_{jk\delta} + \\ \sum_{j\in M} F_jU_j + \sum_{k\in L} G_kV_k + \sum_{i\in N}\sum_{j\in M}\sum_{\delta\in\theta} a_{i\delta}d_{i\delta}(C_{ij}+P_{j\delta})X_{ij\delta} + \\ \sum_{j\in M}\left(\sum_{k\in L}Q1_{kj} + \sum_{i\in N}Q2_{ji} + \sum_{i\in N}Q3_{ij}\right)\beta 2 + \sum_{j\in M}\left(\sum_{k\in L}S1_{kj} + \sum_{i\in N}S2_{ji} + \sum_{i\in N}S3_{ij}\right)\beta 1 \end{aligned} \tag{1}$$

$$\sum_{j\in M}\sum_{\delta\in\theta} X_{ij\delta} = 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{i\in N}\sum_{\delta\in\theta} a_{i\delta}X_{ij\delta} \le b_jU_j \qquad \forall j \in M \tag{3}$$

$$U_j \le 1 \qquad \forall j \in M \tag{4}$$

$$\sum_{i\in N} a_{i\delta}X_{ij\delta} \le \sum_{k\in L} b_jY_{jk\delta} \qquad \forall j \in M,\ \delta \in \theta \tag{5}$$

$$\sum_{j\in M}\sum_{\delta\in\theta} b_jY_{jk\delta} \le e_kV_k \qquad \forall k \in L \tag{6}$$

$$V_k \le 1 \qquad \forall k \in L \tag{7}$$

$$\sum_{\delta\in\theta} a_{i\delta}X_{ij\delta} \le Q2_{ji}\alpha 2 + S2_{ji}\alpha 1 \qquad \forall i \in N,\ \forall j \in M \tag{8}$$

$$b_j\sum_{\delta\in\theta} Y_{jk\delta} \le Q1_{kj}\alpha 2 + S1_{kj}\alpha 1 \qquad \forall k \in L,\ \forall j \in M \tag{9}$$

$$\sum_{\delta\in\theta} d_{i\delta} a_{i\delta} \le \sum_{j\in M} Q3_{ij}\alpha 2 + \sum_{j\in M} S3_{ij}\alpha 1 \qquad \forall i \in N \qquad (10)$$

$$X_{ij\delta} \ge 0 \qquad \forall i \in N,\ j \in M,\ \delta \in \theta \qquad (11)$$

$$Y_{jk\delta} \ge 0 \qquad \forall k \in L,\ j \in M,\ \delta \in \theta \qquad (12)$$

$$Q1_{kj}, Q2_{ji}, Q3_{ij}, S1_{kj}, S2_{ji}, S3_{ij} \ \text{:integer} \qquad \forall k \in L,\ \forall i \in N,\ j \in M \qquad (13)$$

$$U_j, V_k \in \{0,1\} \qquad \forall k \in L,\ j \in M \qquad (14)$$

The model minimizes total costs consisting of: the costs to serve the demands of customers from the warehouses/disposal centers, the costs of shipments from the plants to the warehouses/disposal centers, the costs of producing green products, the costs associated with opening and operating the warehouses/disposal centers and the plants, the costs of shipment and disposal of returned products, the cost of renting big vehicles, and the cost of renting small vehicles. Constraint set (2) ensures that the demands of all customers for all levels of greenness are satisfied by open warehouses/disposal centers. Constraint sets (3) and (5) guarantee that the total customer demands satisfied by an open warehouse/disposal center do not exceed both the capacity of the warehouse/disposal center and the total shipments to the warehouse/disposal center from all open plants, respectively. Constraint set (4) and (7) ensure that at most one warehouse/disposal center and one plant, respectively, can be assigned to each site. Constraints in set (6) represent the capacity restrictions of the plants in terms of their total shipments to the warehouses/disposal centers. Constraint (8) ensures that the demand of each customer zone satisfied by each warehouse/disposal center is less than the capacity assigned to vehicles for this issue. Constraint (9) assures that the shipment from plant at site k to warehouse/disposal center at site j is lesser than the capacity assigned to vehicles for this purpose. Constraint (10) ensures that the capacity of vehicles assigned to returned products from each customer to warehouse/disposal centers in the reverse flow are greater than the returned products. Finally, constraints in sets (11)-(14) enforce the restrictions on the corresponding decision variables.

4-A Real Example

To validate the model, it was tested it on a problem with 6 customers, 3 warehouse-disposal centers, 3 plants and 3 levels of greenness. The coordination of the customers, plants and warehouse-disposal centers are assumed to be based on table 1.

Table 1:
The coordinates of nodes for the real example on x and y axis

	Coordinate (km)					
node	i		j		k	
	x	y	x	y	x	y
1	10	30	5	23	2	23
2	12	22	13	26	13	6
3	15	25	21	5	14	36
4	3	24				
5	12	25				
6	14	34				

Table 2:
Distance between customers and warehouse-disposal centers

	d_{ij}		
i		j	
	1	2	3
1	12	7	36
2	8	5	26
3	12	3	26
4	3	12	37
5	9	2	29
6	20	9	36

To better understand the coordination of the nodes, we implemented the test problem on a real case. We choose the city of Rasht, one of the major cities of Iran, to evaluate the ability of the model. The following map shows the customers, plants and warehouses in this city. We calculate the distances between each pair of nodes using the coordinate distance (tables 2 and 3).

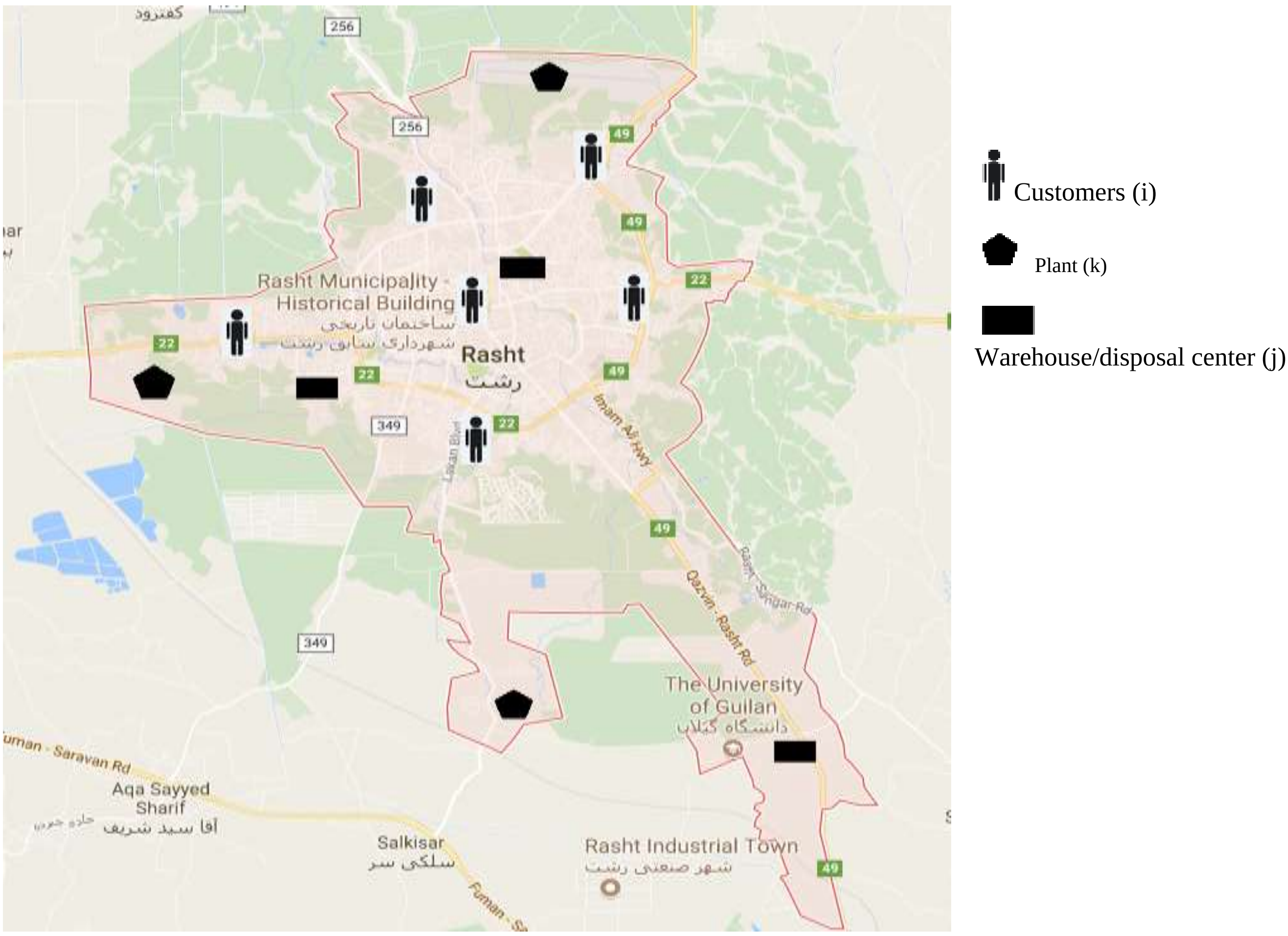


Fig.2. the coordinates of nodes on the map

Table 3:
Distance between warehouse-disposal centers

	d_{jk}			
j		k		
		1	2	3
1		3	25	22
2		14	20	11
3		37	9	38

Table 4:
Transportation cost between customers and warehouse-disposal centers (km)

c_{ij}				
i		j		
		1	2	3
1		108	63	324
2		72	45	234
3		108	27	234
4		27	108	333
5		81	18	261
6		180	81	324

Table 5:
Transportation cost between warehouse-disposal centers and plants

$\bar{C}_{jk}$				
j		k		
		1	2	3
1		21	175	154
2		98	140	77
3		259	63	266

The values of other parameters are generated uniformly as shown in table 6. The problem is solved using the GAMS23.5 on a COREi7 system with 6GB RAM. The results showed that one plant and one warehouse-disposal center which have the minimum vertical coordinates are not selected due to large distance costs. Figure 3 shows the unselected centers in red.

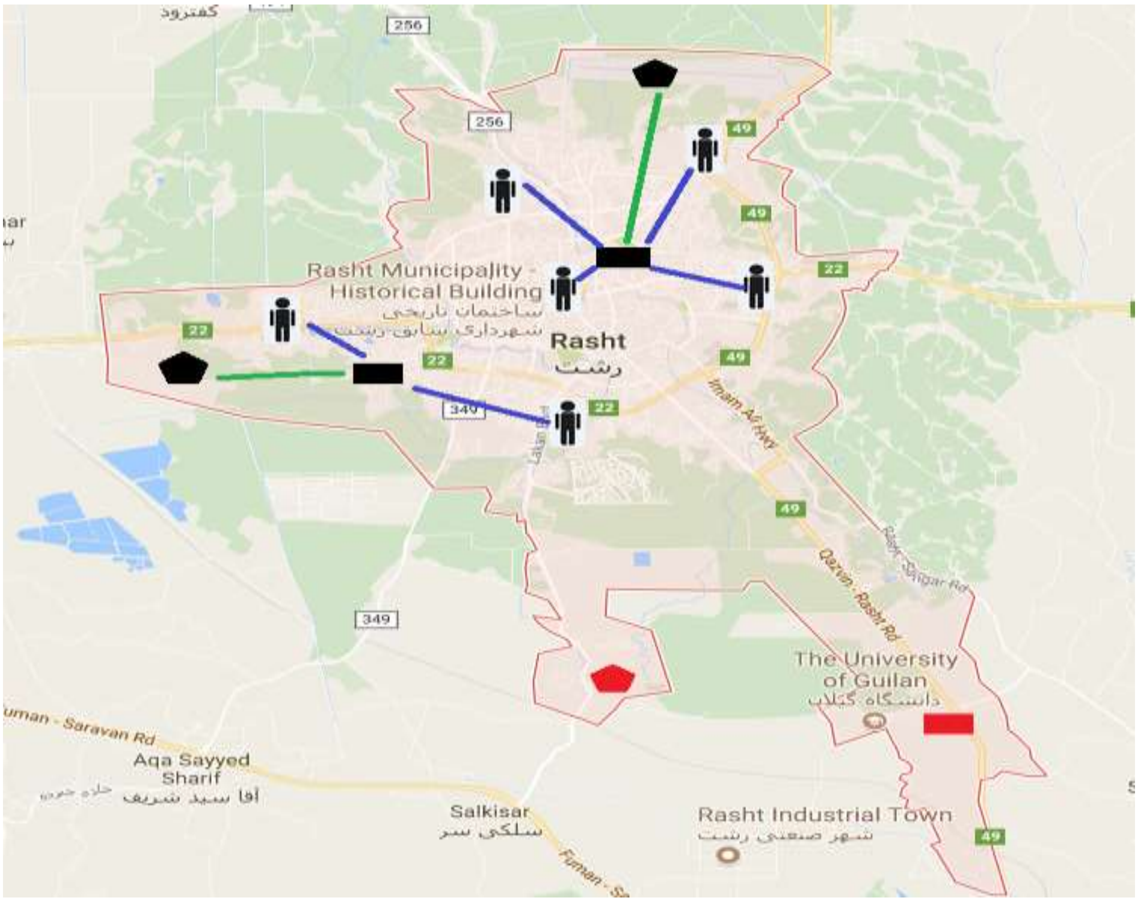


Fig. 3. The network of the problem and unselected nodes in red for the real example

Solution Approach

The proposed problem is a mixed-integer programming problem which which is well known to be an NP-hard problem (Gourdin, Labbé, & Laporte, 2000). Gams can solve small problems; however, for reasonably sized instances computational times with such software become prohibitive. For this reason, we will adopt a method based on the well-established Lagrangian relaxation technique (Fisher, 2004) e to solve the problem.

Relaxation and Lower Bound

Relaxing the set of constraint (6) using Lagrange multipliers λ_k yields the following sub problem and then a lower bound for objective function.

$$Z = Min\sum_{i\in N}\sum_{j\in M}\sum_{\delta\in\theta} C_{ij} a_{i\delta} X_{ij\delta} + \sum_{j\in M}\sum_{k\in L}\sum_{\delta\in\theta} \bar{C}_{jk} b_j Y_{jk\delta} + \sum_{j\in M}\sum_{k\in L}\sum_{\delta\in\theta}\left(\frac{\eta_k}{2}\delta^2\right) b_j Y_{jk\delta} +$$
$$\sum_{j\in M} F_j U_j + \sum_{k\in L} G_k V_k + \sum_{i\in N}\sum_{j\in M}\sum_{\delta\in\theta} a_{i\delta} d_{i\delta}(C_{ij}+P_{j\delta}) X_{ij\delta} +$$
$$\sum_{j\in M}\left(\sum_{k\in L} Q1_{kj} + \sum_{i\in N} Q2_{ji} + \sum_{i\in N} Q3_{ij}\right)\beta 2 + \sum_{j\in M}\left(\sum_{k\in L} S1_{kj} + \sum_{i\in N} S2_{ji} + \sum_{i\in N} S3_{ij}\right)\beta 1 +$$
$$\sum_{k\in L}\left(\left(\sum_{j\in M}\sum_{\delta\in\theta} b_j Y_{jk\delta}\right) - e_k V_k\right)\lambda_k$$

Subject to (2)-(5) and (7)-(14) and

$$\sum_{j\in M}\sum_{\delta\in\theta} b_j Y_{jk\delta} \le e_k$$

At each iteration of the Lagrangian procedure, a lower and an upper bound are obtained. The solution of the aforementioned model provides a lower bound. If the solution is feasible, it also provides an upper bound, which is optimal for the original problem. Otherwise, if the solution is infeasible, we construct a feasible solution which becomes an upper bound using the maximum value of ten times solving the relaxed model.

Multiplier Iinitiation and Updating

The performance of Lagrangian relaxation algorithms can be sensitive to the choice of initial multipliers. In order to obtain a good initial multiplier, we examined the final multipliers of the cases where the problem was solved to optimality.

Once the algorithm starts running, at each iteration k, we use subgradient optimization to update λ by setting

$$\lambda_i^{k+1} = \max\left\{0, \lambda_i^k + T^k G_i^k\right\}$$

where T^k is a step size

$$T^k = \frac{\pi^k \left(Z^* - Z\left(\lambda^k\right)\right)}{\sum_i \left(G_i^k\right)^2}$$

And G_i^k is

$$G_i^k = b_i - \sum_j a_{ij} x_j^k \qquad \forall i$$

In the above formula, π^k is a constant at iteration k, initially set to π^k = 2. We divided the values of π^k by 2 when every 60 consecutive iterations fail to improve the lower bound. Also, z* is the upper bound, and $Z\left(\lambda^k\right)$ is the lower bound when the multipliers are equal to λ^k. The algorithm ends when any of the following criteria are met:

- $\left(Z^* - Z\left(\lambda^k\right)\right) / Z^* \leq \varepsilon$, for some optimality tolerance ε, specified by the user,
- $k > k_{\max}$, for some iteration limit k_{max}.

Finding an Upper Bound

In most cases, the solution obtained from solving Lagrangian problem is infeasible due to relaxing constrain (6). A feasible solution can be found as follows. We solve the basic minimization model under all of the constraints when setting the decision variables $X_{ij\delta}$ equal to optimal values obtained from solving the Lagrangian problem. The resulting feasible solution provides an upper bound for the model.

Computational Results

The problem is tested on a number of test problems in which the parameters are generated based on Table 6.

Table 6:
Data generation for the parameters

b	uniform(4000,5000);
e	uniform(1000,1200);
f	uniform(1000,1200);
g	uniform(1300,1500);
$\bar{C}$	uniform(100,110);
c	uniform(130,150);
η	uniform(500,600);
p	uniform(200,300);
a	uniform(2,3);
d	uniform(0.1,0.2);
$\alpha 1$	80
$\alpha 2$	120
$\beta 1$	1200
$\beta 2$	1800

The problem is tested on different size problems as illustrated in the Table 7.
The Lagrangian relaxed problem is solved using GAMS23.5 on a COREi7 system with 6GB RAM. As discussed the upper bound solves the basic minimization model under all of the constraints when setting the decision. variables $X_{ij\delta}$ equal to optimal values obtained from solving the Lagrangian problem.

Table 7:
Performance of the solution approaches on different test problems

Test problem	Size of the problem				Upper bound	Lower bound	GAMS	Lagrangian Time (s)
	i	j	k	δ				
1	6	3	3	3	15419	15419	15419	13
2	8	4	4	3	22969	22969	22969	14
3	15	6	5	3	60912	60102	60363	18
4	30	10	8	3	177201	171475	175126	26
5	50	14	12	4	488918	475236	479019	48
6	75	20	18	4	984041	957322	-	112
7	100	25	20	5	2081630	2021059	-	413
8	150	30	25	5	3588533	3484984	-	1453
9	200	35	30	5	6172871	5993176	-	4863
10	250	40	35	5	10618275	10308975	-	16982

The results show that the Lagrangian Relaxation approach obtains the solution for even large size problems in relatively short time. The following figure shows the solution approaches performance.

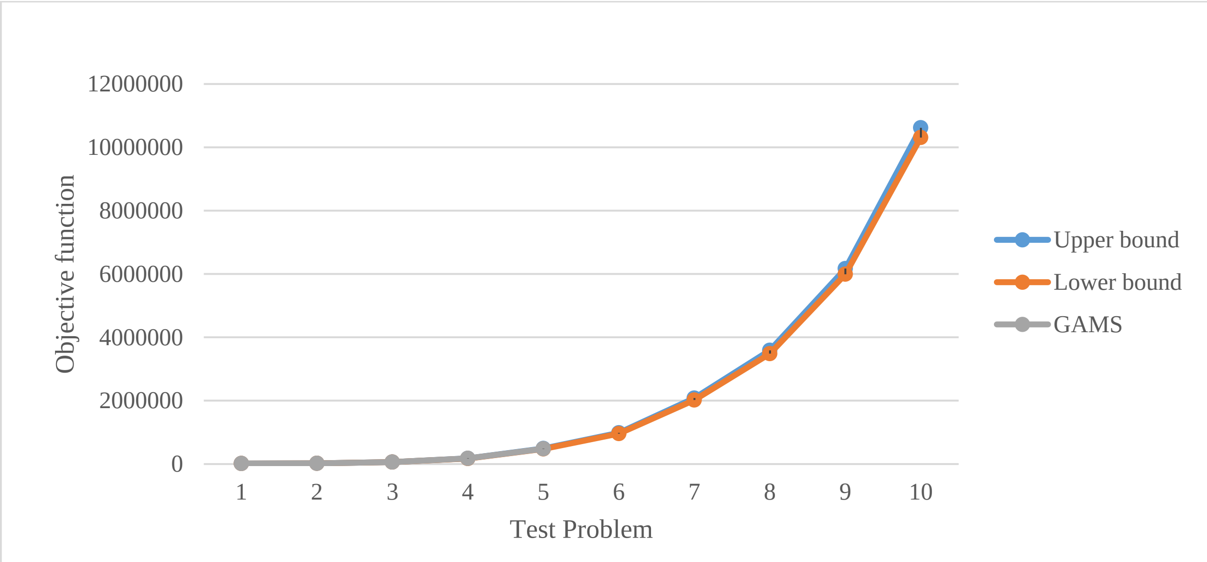


Fig.4. Performance of the solution approaches

Sensitivity analysis and managerial insights

From the management perspective, this model can help the industries which concerned about greenness such that to provide an efficient tradeoff between the costs of different levels of greenness and the passion of distinctive customer segments for green products. In order to analyze the variation of objective function versus cost coefficient of the green degree the following sensitivity analysis is conducted for the first sample problem i.e. six customer zones, three warehouse/disposal centers, three plants and three level of greenness.

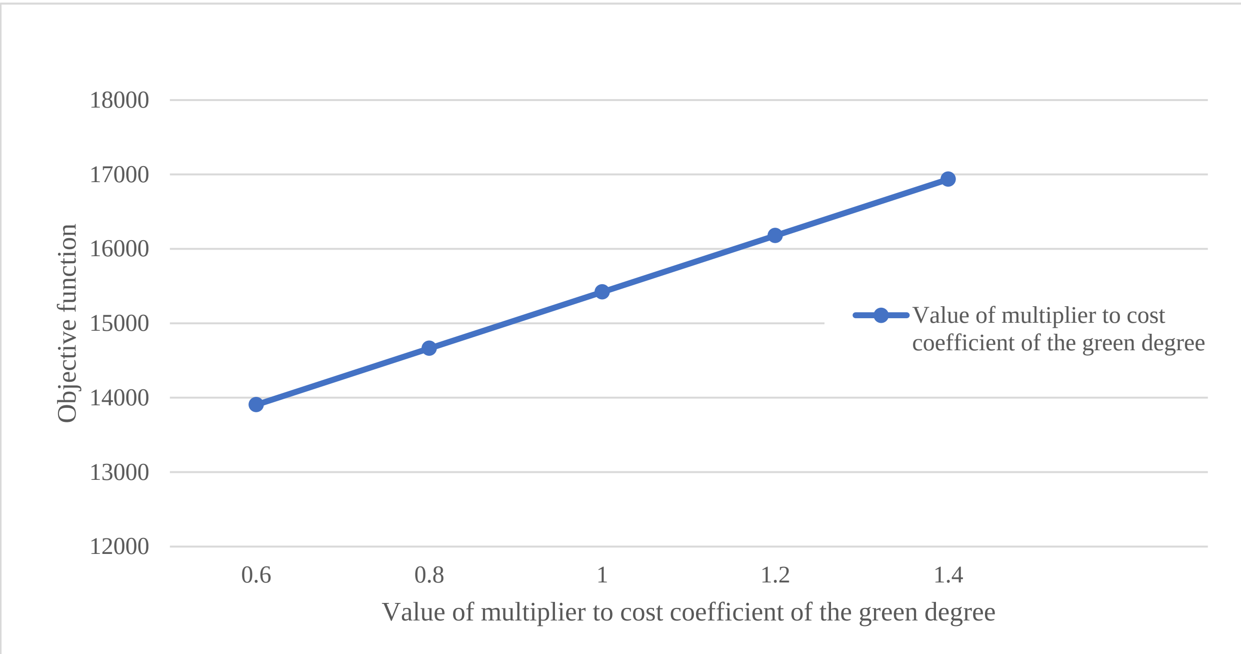


Fig.5.Objective function versus the value of multiplier to cost coefficient of the green degree

References

[1] Agi, M. A., & Yan, X. (2020). Greening products in a supply chain under market segmentation and different channel power structures. *International Journal of Production Economics*, *223*, 107523.

[2] Amiri, A. (2006). Designing a distribution network in a supply chain system: Formulation and efficient solution procedure. *European Journal of Operational Research*, *171*(2), 567–576.

Askin, R. G., Baffo, I., & Xia, M. (2014). Multi-commodity warehouse location and distribution planning with inventory consideration. *International Journal of Production Research*, *52*(7), 1897–1910.

[3] Avella, P., Benati, S., Cánovas Martinez, L., Dalby, K., Di Girolamo, D., Dimitrijevic, B., … Zidda, P. (1998). Some personal views on the current state and the future of locational analysis. *European Journal of Operational Research*, *104*(2), 269–287.

[4] Brahami, M. A., Dahane, M., Souier, M., & Sahnoun, M. H. (2022). Sustainable capacitated facility location/network design problem: a non-dominated sorting genetic algorithm based multiobjective approach. *Annals of Operations Research*, *311*(2), 821-852.

[5] Biswas, A., & Roy, M. (2015). Green products: an exploratory study on the consumer behaviour in emerging economies of the East. *Journal of Cleaner Production*, *87*, 463–468.

[6] Chekima, B., Syed Khalid Wafa, S. A. W., Igau, O. A., Chekima, S., & Sondoh, S. L. (2016). Examining green consumerism motivational drivers: does premium price and demographics matter to green purchasing? *Journal of Cleaner Production*, *112*, 3436–3450.

[7] Conrad, K. (2005). Price Competition and Product Differentiation When Consumers Care for the Environment. *Environmental & Resource Economics*, *31*(1), 1–19.

[8] Coskun, S., Ozgur, L., Polat, O., & Gungor, A. (2016). A model proposal for green supply chain network design based on consumer segmentation. Journal of cleaner production, 110, 149-157.

[9] De Giovanni, P., Reddy, P. V., & Zaccour, G. (2016). Incentive strategies for an optimal recovery program in a closed-loop supply chain. *European Journal of Operational Research*, *249*(2), 605–617.

[10] Dondo, R. G., & Méndez, C. A. (2016). Operational planning of forward and reverse logistic activities on multi-echelon supply-chain networks. *Computers & Chemical Engineering*, *88*, 170–184.

[11] Droste, N., Hansjürgens, B., Kuikman, P., Otter, N., Antikainen, R., Leskinen, P., … Thomsen, M. (2016). Steering innovations towards a green economy: Understanding government intervention. *Journal of Cleaner Production*, *135*, 426–434.

[12] El Saadany, A. M. A., & Jaber, M. Y. (2010). A production/remanufacturing inventory model with price and quality dependant return rate. *Computers & Industrial Engineering*, *58*(3), 352–362.

[13] Farahani, R. Z., Hekmatfar, M., Fahimnia, B., & Kazemzadeh, N. (2014). Hierarchical facility location problem: Models, classifications, techniques, and applications. *Computers & Industrial Engineering*, *68*, 104–117.

[14] Fernandes, D. R. M., Rocha, C., Aloise, D., Ribeiro, G. M., Santos, E. M., & Silva, A. (2014). A simple and effective genetic algorithm for the two-stage capacitated facility location problem. *Computers & Industrial Engineering*, *75*, 200–208.

[15] Fisher, M. L. (2004). The Lagrangian relaxation method for solving integer programming problems. *Management science*, *50*(12_supplement), 1861-1871.

[16] Ghosh, D., & Shah, J. (2012). A comparative analysis of greening policies across supply chain structures. *International Journal of Production Economics*, *135*(2), 568–583.

[17] Ghosh, D., & Shah, J. (2015). Supply chain analysis under green sensitive consumer demand and cost sharing contract. *International Journal of Production Economics*, *164*, 319–329.

[18] Gourdin, É., Labbé, M., & Laporte, G. (2000). The Uncapacitated Facility Location Problem with Client Matching. *Operations Research*, *48*(5), 671–685.

[19] Govindan, K., Azevedo, S. G., Carvalho, H., & Cruz-Machado, V. (2014). Impact of supply chain management practices on sustainability. *Journal of Cleaner Production*, *85*, 212–225.

[20] Guastaroba, G., & Speranza, M. G. (2014). A heuristic for BILP problems: The Single Source Capacitated Facility Location Problem. *European Journal of Operational Research*, *238*(2), 438–450.

[21] Haytko, D. L., & Matulich, E. (2008). Green advertising and environmentally responsible consumer behaviors: Linkages examined. *Journal of Management and Marketing Research*, *1*(1), 2–11.

[22] Jayaraman, V. (1998). An Efficient Heuristic Procedure for Practical-Sized Capacitated Warehouse Design and Management. *Decision Sciences*, *29*(3), 729–745. http://doi.org/10.1111/j.1540-5915.1998.tb01361.x

[23] Jayaraman, V., & Yadong Luo, Y. (2007). Creating Competitive Advantages Through New Value

Creation: A Reverse Logistics Perspective. *Academy of Management Perspectives*, *21*(2), 56–73.

[24] Jeihoonian, M., Kazemi Zanjani, M., & Gendreau, M. (2016). Accelerating Benders decomposition for closed-loop supply chain network design: Case of used durable products with different quality levels. *European Journal of Operational Research*, *251*(3), 830–845.

[25] Ko, H. J., & Evans, G. W. (2007). A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs. *Computers & Operations Research*, *34*(2), 346–366.

[26] Kratica, J., Dugošija, D., & Savić, A. (2014). A new mixed integer linear programming model for the multi level uncapacitated facility location problem. *Applied Mathematical Modelling*, *38*(7-8), 2118-2129.

[27] Kumar, S., & Putnam, V. (2008). Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors. *International Journal of Production Economics*, *115*(2), 305–315.

[28] Mirmajlesi, S. R., & Shafaei, R. (2016). An integrated approach to solve a robust forward/reverse supply chain for short lifetime products. *Computers & Industrial Engineering*, *97*, 222–239.

[29] Mohammad Nezhad, A., Manzour, H., & Salhi, S. (2013). Lagrangian relaxation heuristics for the uncapacitated single-source multi-product facility location problem. *International Journal of Production Economics*, *145*(2), 713–723.

[30] Pati, R., Vrat, P., & Kumar, P. (2008). A goal programming model for paper recycling system. *Omega*, *36*(3), 405–417.

[31] Peng, H., & Peng, H. (2013). Optimal subsidy policy for accelerating the diffusion of green products. *Journal of Industrial Engineering and Management*, *6*(2), 626–641.

[32] Peterson, S. B., & Michalek, J. J. (2013). Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. *Energy Policy*, *52*, 429–438. ht

[33] Pirkul, H., & Jayaraman, V. (1998). A multi-commodity, multi-plant, capacitated facility location problem: formulation and efficient heuristic solution. *Computers & Operations Research*, *25*(10), 869–878.

[34] Rahmani, A., & MirHassani, S. A. (2014). A hybrid Firefly-Genetic Algorithm for the capacitated facility location problem. *Information Sciences*, *283*, 70–78.

[35] Roosta, S., Mirnajafizadeh, S., & Harandi, H. (2023). Development of a robust multi-objective model for green capacitated location-routing under crisis conditions. *Journal of Project Management*, *8*(1), 1-24.

[36] Srivastava, S. K., & Srivastava, R. K. (2006). Managing product returns for reverse logistics. *International Journal of Physical Distribution & Logistics Management*, *36*(7), 524–546.

[37] Swami, S., & Shah, J. (2013). Channel coordination in green supply chain management. *Journal of the Operational Research Society*, *64*(3), 336–351.

[38] Toro, E. M., Franco, J. F., Echeverri, M. G., & Guimarães, F. G. (2017). A multi-objective model for the green capacitated location-routing problem considering environmental impact. *Computers & Industrial Engineering*, *110*, 114–125.

[39] Tsao, Y. C., Raj, P. V. R. P., & Yu, V. (2019). Product substitution in different weights and brands considering customer segmentation and panic buying behavior. *Industrial Marketing Management*, *77*, 209-220.

[40] Tragantalerngsak, S., Holt, J., & Rönnqvist, M. (2000). An exact method for the two-echelon, single-source, capacitated facility location problem. *European Journal of Operational Research*, *123*(3), 473–489.

[41] Xia, L., & He, L. (2014). Game Theoretic Analysis of Carbon Emission Reduction and Sales Promotion in Dyadic Supply Chain in Presence of Consumers' Low-Carbon Awareness. *Discrete Dynamics in Nature and Society*, *2014*, 1–13.

[42] Yilmaz, S., Chanez, C., Cuony, P., & Patel, M. K. (2022). Analysing utility-based direct load control programmes for heat pumps and electric vehicles considering customer segmentation. *Energy Policy*, *164*, 112900.

[43] Yousefi-Babadi, A., Soleimani, N., & Shishebori, D. (2021). Capacitated Sustainable Resilient Closed-Loop Supply Chain Network Design: A Heuristics Algorithm. *Advances in Industrial Engineering*, *55*(4), 447-479..

[44] Zhang, L., Wang, J., & You, J. (2015). Consumer environmental awareness and channel coordination with two substitutable products. *European Journal of Operational Research*, *241*(1), 63–73