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Developing a Bi-objective Mathematical Model to Design the Fish Closed-loop Supply Chain

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ABSTRACT

In recent years, many industries in developed countries have integrated the important process of reverse logistics into their supply chain for different reasons, including growing environmental concerns. Given fish as perishable food, re-employing unused products and waste in each step of the chain constitute a major concern for the decision-makers. The present study is conducted to maximize responsiveness to customer demand and minimize the cost of the fish closed-loop supply chain (CLSC) by proposing a novel mathematical model. To solve this model, the epsilon-constraint method and Lp-metric were employed. Then, the solution methods were compared with each other based on the performance metrics and a statistical hypothesis. The superior method is ultimately determined using the TOPSIS method. The model application is tested on a case study of the trout CLSC in the north of Iran by performing a sensitivity analysis of demand. This analysis showed the promising results of using the proposed solution method and model.

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1. INTRODUCTION

In its classical forward form, a supply chain refers to a combination of processes that aims at meeting customer requirements. These processes include all the possible entities, such as warehouses, retailers, transporters, manufacturers, suppliers, and customers [1]. Although this type of supply chain is not in charge of end-of-life products, a reverse supply chain or reverse logistics seeks to account for end-of-life products [2]. A closed-loop supply chain (CLSC) is a network that comprises both forward and reverse supply chains to add value throughout the life cycle of products [3]. Organizations focused on reverse logistics processes consider it as effective processes since the concept of reverse logistics enhances the economic value of consumption while considering environmental aspects [4, 5].

The scarcity of the earth's resources is well known today, and catastrophic consequences would bring about in case humans continue to be as wasteful as before. The growing population of the world has also exacerbated nutritional problems in communities. Previous food supply chains should be therefore modified in a way that they satisfy today's growing demand [6]. Nowadays, seafood and the associated products account for a major portion of the household consumption basket in different countries. In 2018, the Food and Agriculture Organization (FAO) highlighted the effects of optimization on fish farming [7]. The Iranian Fisheries Organization and the FAO have reported the growing rate of cold-water fish production in Iran. Trout is considered the most well-known fish species among all the numerous species [8].

A global decrease in aquaculture resources and increasing production costs require more attention to the processes and wastes in the aquaculture industry. Implementing reverse logistics in the fish supply chain is therefore crucial. To the best of the authors' knowledge, the present research pioneers the investigation of implementing reverse logistics in fish supply chains. A

network is first developed for the fish CLSC. As a common recycling method of fish waste, fish powder production is performed to produce huge amounts of organic fish food, maintain human health, and preserve the environment. Therefore, this study uses fish waste recycling facilities to perform reverse logistics. A novel mathematical model has also been developed to minimize the cost of the fish CLSC and maximize the responsiveness of customer demand in forward and reverse supply chains. The model is validated by examining an actual application of the method in a case study. Moreover, the epsilon-constraint and Lp-metrics are employed to solve the present multi-objective decision making problem of six different sizes in Lingo. The two methods are compared in terms of their average outcome and based on three prespecified criteria and ranked using the TOPSIS method.

The following sections of this paper are organized as follows. Sections 2 and 3 present a review of the literature and details the mathematical model, respectively. Section 4 presents the solution techniques and section 5 describes their performance metrics and compares the model results between the two methods. Section 6 presents a case study and numerical examples of the trout supply chain in Mazandaran province, Iran. Section 7 presents the computational results. Section 8 ranks the solution methods in terms of the metric measures by employing a multi-criteria decision-making technique. A sensitivity analysis is conducted in section 9, and conclusions and propositions are ultimately made for further studies in section 10.

2. LITERATURE REVIEW

Manufacturing costs can be effectively minimized in competitive markets by managing supply chains. The public, academia, and industrial practitioners have recently paid much attention to reverse logistics and CLSCs [9–13]. The present study focused on fish supply chains by first reviewing cold supply chains and perishable foods. The management and design of food supply chains are significantly affected by perishability [14]. In 1963, Ghare [15] pioneered the investigation of perishability and found the inventory decay to significantly influence the total inventory cost if it is included in the inventory analysis. Perishability has also attracted the attention of researchers and practitioners in the field of supply chains [16]. The management of the supply chains of perishable products has been investigated in review articles [17, 18].

Numerous studies have addressed the efficiency maximization of food supply chains by proposing diverse methods [16]. Exact and metaheuristic algorithms were employed by Mirmajlesi and Shafaei [19] to manage a multi-echelon, multi-product, multi-period, and capacitated supply chain of short-lifetime products.

Abedi and Zhu [20] optimized fish farming, the purchase of spawn, and the distribution of harvested fish in a fish supply chain by developing a mixed-integer linear programming model for the maximization of the total profit. An inventory routing problem with environmental constraints on food was solved by Soysal et al. [21]. Cheraghalipour et al. [22] developed a multi-period, single-product, and multi-objective programming model and designed a CLSC for citrus. Metaheuristic algorithms were also employed to decrease the burden of computation in actual problems. Tabrizi et al. [14] investigated equilibrium models in perishable food supply chains by proposing a novel optimization model and performing a case study of the supply chain of warm-water farmed fish.

Masruroh et al. [23] proposed an integrated multi-product distribution allocation and production planning for a dairy supply chain. Onggo et al. [24] solved a perishable inventory routing problem with probabilistic demand using a mixed-integer programming model and a simheuristic algorithm comprising an iterated local search and Monte Carlo simulation. Naderi et al. [25] studied the wheat supply chain network design (SCND) as a case study considering capacity and fleet management. Also, Motevalli-Taher et al. [26] optimized the wheat SCND considering the sustainability criteria and uncertainty. Leng et al. [27] minimized the total logistics cost and vehicle and client waiting times by proposing a comprehensive low-carbon cold-chain based location-routing model. Chan et al. [28] used multi-objective mixed-integer linear programming for smart food logistics systems. Several review studies have been also performed on perishable food supply chains [29–31].

3. MATHEMATICAL MODELING

3. 1. Problem Statement   The present research design a CLSC for fish logistic networks. The designed logistics network is single-period, including producers (Pool-Farm, Rice-Farm, and Sea-Farm) as can be seen in Figure 1, distribution centers, reprocessing centers (fish powder centers), processing centers (processed fish centers), and customers (markets: fresh fish markets, processed fish markets, and fish powder markets).

Figure 2 shows the forward flow, in which goods are transported from producers to distribution centers and customers, and from distribution centers to customers to satisfy their unsupplied demand by producers. Fixed
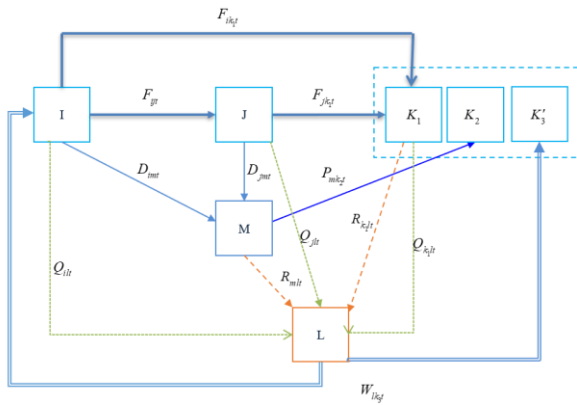

Figure 1. Fish farms

Figure 2. Flowchart for the fish CLSC

locations are also assumed for processing centers and customers. Producer locations and distribution and reprocessing centers can include fixed or potential points of the locations. The products returned in the reverse flow are shipped to reprocessing centers to be converted to byproducts and again are shipped to the customers of the fish powder market. Given farms (producers) as the potential customers of fish feed, the network can be considered a CLSC where producers play the role of fish powder customers. Significant reductions in product life, natural resources, and landfills have turned waste management into an important problem. A dedicated recovery plan should be assigned to individual end-of-life products given their dissimilarity [32].

The present research designed a CLSC for farmed fish in forward and reverse flow modes by developing a bi-objective mathematical model. The chain cost was minimized and responsiveness to customer demand maximized by collecting the fish waste and losses in the fish supply chain using a network.

3. 2. Notations

Indices

$i_1 = 1, 2, ..., I_1$	Production locations (Pool-Farm)- Fixed points
$i_2 = 1, 2, ..., I_2$	Production locations (Rice-Farm)- Potential points
$i_3 = 1, 2, ..., I_3$	Production locations (Sea-Farm)- Potential points
$i = i_1 + i_2 + i_3$	Production locations (fish farms)- All points
$j_1 = 1, 2, ..., J_1$	Distribution locations- Fixed points
$j_2 = 1, 2, ..., J_2$	Distribution locations- Potential points
$j = j_1 + j_2$	Distribution locations- All points
$k_1 = 1, 2, ..., K_1$	Customer locations (fresh fish markets)
$k_2 = 1, 2, ..., K_2$	Customer locations (processed fish markets)
$k_3' = 1, 2, ..., K_3'$	Customer locations (fish powder markets)
$k_3'' = 1, 2, ..., K_3''$	Some of the producers (fish farms) as fish powder's customers

$k_3 = k_3' + k_3''$	Fish powder customer locations
$l_1 = 1, 2, ..., L_1$	The fish waste recycling center locations- Fixed points
$l_2 = 1, 2, ..., L_2$	Fish waste recycling center locations- Potential points
$l = l_1 + l_2$	Fish waste recycling center locations- All points
$m = 1, 2, ..., M$	Fish processing center locations

Parameters

f_i	Fixed cost required for opening production center i
f_j	Fixed cost required for opening distribution center j
f_l	Fixed cost required for opening fish waste recycling center l
Cf_{ij}	Shipping cost per unit of live products from producer i to distribution center j
Cf_{ik_1}	Shipping cost per unit of fresh products from producer i to customer k_1
Cf_{jk_1}	Shipping cost per unit of fresh products from distribution center j to customer k_1
Cd_{im}	Shipping cost per unit of fresh products from producer i to fish processing center m
Cd_{jm}	Shipping cost per unit of fresh products from distribution center j fish processing center m
Cp_{mk_2}	Shipping cost per unit of processed products from fish processing center m to customer k_2
Cr_{k_1l}	Shipping cost per unit of waste products from customer k_1 to fish waste recycling center l
Cr_{ml}	Shipping cost per unit of waste products fish processing center m to fish waste recycling center l
Cw_{lk_3}	Shipping cost per unit of reprocessed products from fish waste recycling center l to fish powder markets k_3
Cq_{il}	Shipping cost per unit of low-quality products from producer i to fish waste recycling center l
Cq_{jl}	Shipping cost per unit of low-quality products from distribution center j fish waste recycling center l
Cq_{k_1l}	Shipping cost per unit of low-quality products from customer k_1 fish waste recycling center l
Cp	Processing cost per unit of products from fish processing centers
Cr	Fish powder manufacturing cost per unit of products from fish waste recycling centers
Cp'	Production cost per unit of products from producers
d_{k_1}	Demand of fresh product by the customer k_1
d_{k_2}	Demand of processed product by the customer k_2
d_{k_3}	Demand of reprocessed product (fish powder) by fish powder markets k_3
λc_i	Maximum production capacity of producer i
λh_j	Holding capacity of distribution center j
λr_l	Fish powder manufacturing capacity of fish waste recycling center l
λr_m	Processing capacity of fish processing center m
α_i	Deteriorating percentage of the product by producers
α_j	Deteriorating percentage of the product by distribution centers

α_{k_1}	Deteriorating percentage of the product by the customer k_1
β_{k_1}	Waste percentage of the product by the customer k_1
β_m	Waste percentage of the product by fish processing centers
θ	Minimum rate of using the capacity of each distribution center
δ	Maximum rate of supplying customer demand for fresh fish directly from the producer
ρ	Weighted importance coefficient to make a response the forward flows
$1-\rho$	Weighted importance coefficient to make a response the reverse flows
φ	Conversion rate of the waste product to a reprocessed product (fish powder)
φ'	Conversion rate of a product to a processed product
MM	A big positive number

Decision Variables

F_{ij}	Quantity of live products shipped from producer i to distribution center j
F_{ik_1}	Quantity of fresh products shipped from producer i to customer k_1
F_{jk_1}	Quantity of fresh products shipped from distribution center j to customer k_1
$R_{k_1 l}$	Quantity of waste products shipped from the customer k_1 to fish waste recycling center l
R_{ml}	Quantity of waste products shipped from fish processing center m to fish waste recycling center l
D_{im}	Quantity of fresh products shipped from producer i to fish processing center m
D_{jm}	Quantity of fresh products shipped from distribution center j to fish processing center m
P_{mk_2}	Quantity of processed products shipped from fish processing center m to customer k_2
W_{lk_3}	Quantity of reprocessed products (fish powder) shipped from fish waste recycling centers l to fish powder markets k_3
Q_{il}	Quantity of low-quality products shipped from producer i to fish waste recycling centers l
Q_{jl}	Quantity of low-quality products shipped from distribution center j to fish waste recycling centers l
$Q_{k_1 l}$	Quantity of low-quality products shipped from the customer k_1 to fish waste recycling centers l
λ_i	Quantity of production by producer i
X_i	1 If production center i is opened at the location, 0 otherwise
W_j	1 If distribution center j is opened at the location, 0 otherwise
Y_l	1 If fish waste recycling center l is opened at the location, 0 otherwise

3. 3. Mathematical Model The bi-objective design of the fish CLSC is formulated as folloddws:

$$Min\, Z = z_1 + z_2 + z_3 \qquad (1)$$

$$z_1 = \sum_{i=1}^{I} f_i \times X_i + \sum_{j=1}^{J} f_j \times W_j + \sum_{l=1}^{L} f_l \times Y_l \qquad (2)$$

$$z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J} Cf_{ij} \times F_{ij} + \sum_{j=1}^{J}\sum_{k_1=1}^{K_1} Cf_{jk_1} \times F_{jk_1} + \sum_{i=1}^{I}\sum_{k_1=1}^{K_1} Cf_{ik_1} \times F_{ik_1}$$
$$+ \sum_{i=1}^{I}\sum_{m=1}^{M} Cd_{im} \times D_{im} + \sum_{j=1}^{J}\sum_{m=1}^{M} Cd_{jm} \times D_{jm} + \sum_{m=1}^{M}\sum_{k_2=1}^{K_2} Cp_{mk_2} \times P_{mk_2}$$
$$+ \sum_{m=1}^{M}\sum_{l=1}^{L} Cr_{ml} \times R_{ml} + \sum_{k_1=1}^{K_1}\sum_{l=1}^{L} Cr_{k_1 l} \times R_{k_1 l} \qquad (3)$$
$$+ \sum_{l=1}^{L}\sum_{k_3=1}^{K_3} Cw_{lk_3} \times W_{lk_3}$$
$$+ \sum_{i=1}^{I}\sum_{l=1}^{L} Cq_{il} \times Q_{il} + \sum_{j=1}^{J}\sum_{l=1}^{L} Cq_{jl} \times Q_{jl} + \sum_{k_1=1}^{K_1}\sum_{l=1}^{L} Cq_{k_1 l} \times Q_{k_1 l}$$

$$z_3 = \sum_{m=1}^{M}\sum_{k_2=1}^{K} P_{mk_2} \times Cp + \sum_{l=1}^{L}\sum_{k_3=1}^{K_3} W_{lk_3} \times Cr + \sum_{i=1}^{I} \lambda_i \times Cp' \qquad (4)$$

$$Max\, Z' = (\rho/2) \times \left(\sum_{k_1=1}^{K_1}\sum_{i=1}^{I} F_{ik_1} + \sum_{k_1=1}^{K_1}\sum_{j=1}^{J} F_{jk_1} \middle/ \sum_{k_1=1}^{K_1} d_{k_1} \right)$$
$$+ (\rho/2) \times \left(\sum_{k_2=1}^{K_2}\sum_{m=1}^{M} P_{mk_2} \middle/ \sum_{k_2=1}^{K_2} d_{k_2} \right) \qquad (5)$$
$$+ (1-\rho) \times \left(\sum_{l=1}^{L}\sum_{k_3=1}^{K_3} W_{lk_3} \right) \middle/ \left(\sum_{k_3=1}^{K_3} d_{k_3} \right)$$

The first objective function (Z) is the total cost comprising fixed opening costs, transportation and production costs, and costs of the fish processing centers and waste recycling (reprocessing) centers (2)-(4). The second objective function (Z') with a maximum value of 1 comprises the forward and reverse responsiveness of the closed-loop network. The fraction's numerator and denominator respectively showed the products shipped to customers and customer demand. A zero inventory is initially assumed for all the centers.

Subject to:

$$\lambda_i \times (1-\alpha_i) - \sum_{m=1}^{M} D_{im} = \sum_{j=1}^{J} F_{ij} + \sum_{k_1=1}^{K_1} F_{ik_1} \qquad \forall\, i \in I \qquad (6)$$

$$\sum_{i=1}^{I} F_{ij} \leq MM \times W_j \qquad \forall j \in J \qquad (7)$$

$$\lambda_i \leq \lambda c_i \qquad \forall\, i \in I \qquad (8)$$

$$\sum_{i=1}^{I} F_{ij} \leq \lambda h_j \qquad \forall\, j \in J \qquad (9\text{-}a)$$

$$\sum_{i=1}^{I} F_{ij} \geq \theta \times \lambda h_j \qquad \forall\, j \in J_1 \qquad (9\text{-}b)$$

$$\sum_{i=1}^{I} F_{ij} = \sum_{k_1=1}^{K_1} F_{jk_1} + \sum_{m=1}^{M} D_{jm} + \sum_{l=1}^{L} Q_{jl} \qquad \forall\, j \in J \qquad (10)$$

$$\sum_{j=1}^{J} F_{jk_1} + \sum_{i=1}^{I} F_{ik_1} \leq d_{k_1} \qquad \forall\, k_1 \in K_1 \qquad (11)$$

$$\sum_{i=1}^{I} F_{ik_1} \le \delta \times d_{k_1} \qquad \forall k_1 \in K_1 \tag{12}$$

$$(\sum_{i=1}^{I} D_{im} + \sum_{j=1}^{J} D_{jm} - \sum_{l=1}^{L} R_{ml}) \times \varphi' = \sum_{k_2=1}^{K_2} P_{mk_2} \qquad \forall m \in M \tag{13}$$

$$\sum_{k_2=1}^{K_2} P_{mk_2} \le \lambda r_m \qquad \forall\, m \in M \tag{14}$$

$$\sum_{m=1}^{M} P_{mk_2} \le d_{k_2} \qquad \forall\, k_2 \in K_2 \tag{15}$$

$$\sum_{l=1}^{L} Q_{il} \le \alpha_i \times \lambda_i \qquad \forall i \in I \tag{16}$$

$$\sum_{i=1}^{I} Q_{il} \le MM \times Y_l \qquad \forall l \in L \tag{17}$$

$$\sum_{l=1}^{L} Q_{jl} \le \alpha_j \times \sum_{i=1}^{I} F_{ij} \qquad \forall j \in J \tag{18}$$

$$\sum_{j=1}^{J} Q_{jl} \le MM \times Y_l \qquad \forall l \in L \tag{19}$$

$$\sum_{l=1}^{L} Q_{k_1l} \le \alpha_{k_1} \times (\sum_{i=1}^{I} F_{ik_1} + \sum_{j=1}^{J} F_{jk_1}) \qquad \forall k_1 \in K_1 \tag{20}$$

$$\sum_{k_1=1}^{K_1} Q_{K_1l} \le MM \times Y_l \qquad \forall l \in L \tag{21}$$

$$\sum_{l=1}^{L} R_{k_1l} \le \beta_{k_1} \times (\sum_{i=1}^{I} F_{ik_1} + \sum_{j=1}^{J} F_{jk_1}) \times (1-\alpha_{k_1}) \qquad \forall k_1 \in K_1 \tag{22}$$

$$\sum_{k_1=1}^{K_1} R_{k_1l} \le MM \times Y_l \qquad \forall l \in L \tag{23}$$

$$\sum_{l=1}^{L} R_{ml} \le \beta_m \times (\sum_{i=1}^{I} D_{im} + \sum_{j=1}^{J} D_{jm}) \qquad \forall m \in M \tag{24}$$

$$\sum_{m=1}^{M} R_{ml} \le MM \times Y_l \qquad \forall l \in L \tag{25}$$

$$(\sum_{m=1}^{M} R_{mlt} + \sum_{k_1=1}^{K_1} R_{k_1l} + \sum_{i=1}^{I} Q_{il} + \sum_{j=1}^{J} Q_{jl} + \sum_{k_1=1}^{K_1} Q_{k_1l}) \times \varphi = \sum_{k_3=1}^{K_3} W_{lk_3} \qquad \forall l \in L \tag{26}$$

$$\sum_{k_3=1}^{K_3} W_{lk_3} \le \lambda r_l \qquad \forall l \in L \tag{27}$$

$$\sum_{l=1}^{L} W_{lk_3} \le d_{k_3} \qquad \forall k_3 \in K_3 \tag{28}$$

$$\sum_{j=1}^{J} F_{ij} \le MM \times X_i \qquad \forall i \in I \tag{29}$$

$$\sum_{k_1=1}^{K_1} F_{ik_1} \le MM \times X_i \qquad \forall i \in I \tag{30}$$

$$\sum_{m=1}^{M} D_{im} \le MM \times X_i \qquad \forall i \in I \tag{31}$$

$$\sum_{l=1}^{L} Q_{il} \le MM \times X_i \qquad \forall i \in I \tag{32}$$

$$X_i,\, Y_l,\, W_j \in \{0,1\} \qquad \forall i \in I,\, \forall l \in L,\, \forall j \in J \tag{33}$$

$$F_{ij},F_{ik_1},F_{jk_1},D_{im},D_{jm},R_{k_1l},R_{ml},W_{lk_3},Q_{il},Q_{jl},Q_{k_1l} \ge 0$$
$$\forall i \in I, j \in J, k_1 \in K_1, k_2 \in K_2, k_3 \in K_3, m \in M, l \in L \tag{34}$$

$$\lambda_i \ge 0 \qquad \forall i \in I \tag{35}$$

According to constraint (6), the production level minus the amounts of deteriorated product and that transported to the processing centers equals the number of products transported from the producers to the customers and distribution centers. According to constraint (7), a product is transported to a potential location only if a distribution center is open there. According to constraint (8), the maximum amount of products of a producer, i.e. its production capacity, equals an expected maximum production rate. Constraints (9-a) and (9-b) respectively ensure that the amount of products received from the producers in a distribution center is at most equal to its holding capacity and that a minimum amount of the capacity of a distribution center is used.

According to constraint (10), the amount of products received from the producers in a distribution center equals the sum of the number of products transported to the customers and processing centers and that of deteriorated products transported to the reprocessing centers. Constraint (11) ensures that the demand for a fresh product at least equals the number of products received from the producers and distribution centers. According to constraint (12), the producers directly supply the maximum customer demand for fresh fish. According to constraint (13), all the products received from the distribution centers and producers minus the wasted products transported to the reprocessing centers multiplied by the conversion rate equals the total processed product transported to the processed product market. Constraints (14) and (15) respectively ensure that the amount of products transported to the processed product market is at most equal to the expected maximum processing rate and the customer demand for the processed products.

According to constraint (16), the waste production rate at least equals the amount of returned products transported from the producers to the reprocessing centers. Constraint (17) ensures that the returned products are transported from a production center to a reprocessing center only if a reprocessing center is open in the potential place for this facility. As in the case of constraints (16)-(17), constraints (18)-(19), (20)-(21), (22)-(23) and (24)-(25) put the maximum capacity of the facilities as a limit on the transported products and determine the opening of the facility as a precondition for shipping the goods. According to constraint (26), the total fish powder transported as the reprocessed product to the fish powder market equals all the products returned from the processing centers, producers, customers, and distribution centers multiplied by the conversion rate.

Constraints (27)-(28) respectively ensure that the manufacturing capacity and demand of a fish powder market at least equal the amount of fish powder transported to the fish powder market. According to constraints (29)-(32), the products can be transported to places where there is an open production center. Constraints (33)-(35) also show binary and non-negativity limitations on the associated decision variables.

4. SOLUTION TECHNIQUES

The Lp-metrics and epsilon-constraint detail as follows and are used to solve the multi-objective problem. They are evaluated in terms of their CPU time and solution quality as performance indicators.

4. 1. LP-Metric Method   The metric distance is utilized in Lp-metrics to measure the distance between an existing and the optimal solution [33]. Xu [34] proposed Equation (36) for "the more the better" problems based on an anti-ideal concept.

$$Lp = \left\{ \sum_{j=1}^{k} w_j \left[\frac{f_j(x^{*j}) - f_j(x)}{f_j(x^{*j}) - f_j(\overline{x}^j)} \right]^p \right\}^{1/p} \tag{36}$$

The compatible Lp function is minimized to minimize deviation from the optimal solution. Equation (36) is utilized as a normalized form to obtain the efficiency of the compatible Lp function for various objectives with diverse scales. The decision-maker determines p as the level of emphasis on the available values of deviation. This study assumed p to equal 2. The optimal solution ($f_j(x^{*j})$) is first obtained by individually solving all the objective functions based on the relevant constraints. Anti-ideal values are then obtained by solving the reverse objective functions, i.e. minimization was converted to maximization and vice versa. These values are inserted into the Lp model, which was then minimized based on its constraints. The optimal values and Lp deviation are ultimately obtained through solving the model. With w_j representing the degree of importance of the j-th objective ($\sum_{j=1}^{k} w_j = 1$), the gradual-priority weighting [35] is employed to search the entire solution space, as well as obtaining Pareto-optimal solutions. Equations (37) are used to determine the weights of a generation.

$$\theta_t = \frac{90}{N_s - 1} \times (t-1), \ p_{1t} = \cos(\theta_t), \ p_{2t} = \sin(\theta_t),$$

$$w_{1t} = \frac{p_{1t}}{p_{1t} + p_{2t}}, w_{2t} = \frac{p_{2t}}{p_{1t} + p_{2t}} \quad \forall t = 1, 2, ..., N_s \tag{37}$$

where t is the tth Pareto solution ($t = 1, \dots, 10$).

4. 2. Epsilon-Constraint Method   A maximization multi-objective integer programming problem is considered as follows:

$$\max \ \{f_1(x), f_2(x), ..., f_p(x)\}$$
$$\text{s.t.} \quad x \in S \tag{38}$$

where p represents the number of objective functions, $f_i(x)$ the i-th objective function, , x the decision vector, S the solution space, n the number of decision variables and $x_j \in Z$ for $j \in 1,2, \dots, p$. The conventional epsilon-constraint technique is performed by optimizing an objective function while adding the other objectives into the constraint space to ensure that the basic requirements are met. The method of AUGMECON is employed to convert inequality constraints of the objective functions to equality constraints and obtain efficient solutions through introducing non-negative slack or surplus variables and augmenting the objective function using a weighted sum of the surplus or slack variables [36]. The problem is re-written as follows:

$$\max \ f_p(x) + \delta(s_1/r_1 + s_2/r_2 + ... + s_{p-1}/r_{p-1})$$
$$\text{s.t.} \quad f_1(x) - s_1 = e_1$$
$$\dots \tag{39}$$
$$f_{p-1}(x) - s_{p-1} = e_{p-1}$$
$$x \in S \ \text{and } s_i \in Z^+, i \in [1, p-1]$$

where $r_i, \ i \in [1, p-1]$ represents the range of the i-th objective function, δ an adequately-small value between 10^{-3} and 10^{-6} and $e_1, \dots, e_{p-1}$ the satisfaction level vector showing minimum requirements for the constrained objective functions.

5. PERFORMANCE METRICS

The solution methods were compared with each other in terms of their performance using the following three indicators, each of which appraising a different dimension.
a) Mean ideal distance (MID): This distance defined as Equation (40) is utilized to calculate the distance between the ideal point and Pareto solutions [37]. The method performance was higher at lower values of this index.

$$MID = \frac{\sum_{i=1}^{n} \sqrt{\left(\frac{f1_i - f1_{best}}{f1_{total}^{max} - f1_{total}^{min}}\right)^2 + \left(\frac{f2_i - f2_{best}}{f2_{total}^{max} - f2_{total}^{min}}\right)^2}}{n} \tag{40}$$

where $f1_i$ and $f2_i$ represent the value of the i-th non-dominated solution to the two objective functions, respectively, n is the number of non-dominated solutions, ($f1_{best}$, $f2_{best}$) are the ideal point (i.e., (0, 1) in this study), and fj_{total}^{max} and fj_{total}^{min} are the highest and lowest

values of a fitness function among all the non-dominated solutions, respectively.

b) Rate of achievement to two objectives Simultaneously (RAS): This method introduces a set of solutions to strike a more effective balance between the values of the objective functions as superior Equation (41) shows the extent to which this balance is achieved between different goals [38].

$$RAS = \frac{\sum_{i=1}^{n}\left(\frac{f_{1i}-F_i}{F_i}\right)+\left(\frac{f_{2i}-F_i}{F_i}\right)}{n} \qquad (41)$$

where *n* represents the number of non-defeated solutions and $F_i = \min\{f_{1i}, f_{2i}\}$.

According to the equilibrium method, this criterion increases if a solution along an axis suits one goal and contradicts the other (unbalanced solutions). This study normalized the objective functions to use this criterion.

c) Computational time (CPU time): This index is used for evaluating the running speed of a method.

6. NUMERICAL EXAMPLES AND CASE STUDY

Six problems are generated and tested to examine the performance of the solution techniques. They are categorized by their numbers of producers (*I*), reprocessing centers (*L*), customers (*K₁*), distribution centers (*J*), processing centers (*M*), and customers of processed products (*K₂*) and the fish powder (*K₃*). Table 1 shows the values of these parameters. The first problem is the case study and each problem is simulated ten times to obtain Pareto solutions.

A case study is conducted in Northern Iran to demonstrate the application of the solution method and study model. Different parameters and conditions are considered in using solution methods to examine the proposed model. The data are collected in Mazandaran, Iran. Figure 3 shows the main towns in this province.

The transportation cost is defined between the towns in Iran by their distances in km, fare rates ($ per km), and transport mode (live fish: 1.36, fresh or processed fish: 0.18, and fish powder: $0.09 /ton.km). Table 2 presents the values of the other parameters of the model. Tables 3 and 4, respectively show the selected towns for the

individual places in the case study and their distances. Table 5 presents the model parameters of the case study.

7. COMPUTATIONAL RESULTS

To validate and evaluate the efficiency of the model and compare the two proposed solution methods, the model in six different sizes with Lp-metrics methods and epsilon-constraint was run on a computer with Intel® Core ™ i7-8750H CPU @ 2.20GHz specifications using Lingo software (LINGO 18.0 x64).

The proposed methods were statistically compared with each other by testing the hypothesis of equality of means, comparing the values of the first and second objective functions, and examining the execution time and average results of sixty times of implementing the model for all the three criteria. Testing the hypothesis of equality of means is appropriate for comparing the results of two samples [39]. The null hypothesis suggested the equality of the means of Lp-metrics and epsilon-constraint methods and hypothesis one suggested that their opposite means.

Table 6 presents the results of testing the hypotheses in Minitab 18 at a 95% confidence interval. The null hypothesis is rejected in terms of the computation time of the model and the criterion of the first and second objective functions, which suggested significant differences in the mean values of these criteria between the two methods.

The solution methods are compared with each other by conducting a pairwise comparison based on the metrics proposed in Section 6 (Table 7). The lower values of the metrics suggest an increased performance.

ANOVA is applied to compare the obtained metrics and statistically-significant differences between the methods are shown in terms of their performance. Figure 4 shows the plots of the intervals for each metric used in these methods at a 95% confidence interval. The interval plots are individually obtained for each solution method and metric using six points in Table 7, suggesting that epsilon-constraint outperforms the other method in terms of MID, RAS, and CPU time metrics.

TABLE 1. General data of the test problems

Test #	I_1	I_2	I_3	I	J_1	J_2	J	K_1	K_2	M	L_1	L_2	L	K'_3	K''_3	K_3
1	3	1	1	5	5	1	6	9	2	1	0	2	2	1	2	3
2	4	2	2	8	7	2	9	13	5	2	1	3	4	2	3	5
3	5	3	3	11	9	3	12	17	8	3	2	4	6	3	4	7
4	6	4	4	14	11	4	15	21	11	4	3	5	8	4	5	9
5	7	5	5	17	13	5	18	25	14	5	4	6	10	5	6	11
6	8	6	6	20	15	6	21	29	17	6	5	7	12	6	7	13
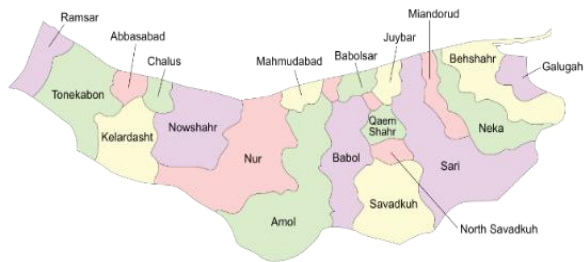
Figure 3. Main towns in Mazandaran

TABLE 2. Other model parameters setting

Parameter	Values	Unit
f_i	Uniform ~ [2.73, 144]	Dollar ($)
f_j	Uniform ~ [48.61, 347]	Dollar ($)
f_l	Uniform ~ [69.44, 190]	Dollar ($)
d_{k_1}	Uniform ~ [0.99, 11]	Ton
d_{k_2}	Uniform ~ [0.66, 2]	Ton
d_{k_3}	Uniform ~ [0.17, 0.4]	Ton
λc_i	Uniform ~ [1.25, 19]	Ton
λh_j	Uniform ~ [0.7, 11]	Ton
λr_m	Uniform ~ [2.78, 6]	Ton
λr_l	Uniform ~ [1.1, 3]	Ton
α_i =0.01, α_j =0.02, α_{k_1} =0.03, β_{k_1} =0.15, β_m = 0.4, θ =0.5, δ =0.2, ρ=0.6, φ=0.25, φ'=1.2		Percentage
Cp =2273, Cr =454, Cp' =909		Dollar per Ton

TABLE 3. Selected cities for each index

i	j	*K1*	*K2*
Tonekabon	Tonekabon	Ramsar	Chalus
Chalus	Abbasabad	Tonekabon	Ramsar
Amol	Noshahr	Kelardasht	
Amol (Rice-farm)	Mahmoodabad	Abbasabad	*K3*
Noshahr (Sea-farm)	Amol	Chalus	Noor
	Chalus	Noshahr	Tonekabon
l		Noor	Amol
Tonekabon	*m*	Mahmoodabad	
Noshahr	Amol	Amol	

TABLE 4. Distance between the mentioned towns (Km)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1)	1	22	46	94	101	133	149	156	181
(2)	22	1	25	73	80	11	128	135	159
(3)	46	25	1	49	55	87	103	110	135
(4)	94	73	49	1	8.1	41	57	64	89
(5)	101	80	55	8.1	1	33	50	56	81
(6)	133	111	87	41	33	1	38	25	49
(7)	149	128	103	57	50	38	g1	61	86
(8)	156	35	110	64	56	25	61	1	25
(9)	181	159	135	89	81	49	86	25	1

(1) Amol, (2) Mahmoodabad, (3) Noor, (4) Noshahr, (5) Chalus, (6) Abbasabad, (7) Kelardasht, (8) Tonekabon, (9) Ramsar.

TABLE 5. Model parameters setting for the case study

Parameter	Values	Unit
f_i	[0, 0, 0, 11.32, 2.73]	Dollar ($)
f_j	[0, 0, 0, 0, 0, 48.61]	Dollar ($)
f_l	[82.07, 69.44]	Dollar ($)
d_{k_1}	[0.99, 2.22, 0.7, 1.85, 1.55, 0.32, 1.62, 1.31, 5.36]	Ton
d_{k_2}	[1.03, 0.66]	Ton
d_{k_3}	[0.17, 0.18, 0.19]	Ton
λc_i	[9.13, 1.25, 9.51, 5.60, 0.36]	Ton
λh_j	[2.2 0.7 1.84 1.30 5.32 1.54]	Ton
λr_m	[2.78]	Ton
λr_l	[1.3, 1.1]	Ton

TABLE 6. Result of the hypothesis test

Method	Obj. 1	Obj. 2	CPU Time
ε-constraint	98,601.1380	0.8762	1.9794
Lp-metrics	74,622.3557	0.7940	25.2738
	Reject H_0	Reject H_0	Reject H_0

8. RANKING THE SOLUTION METHODS

TOPSIS is employed to determine the performance of the solution methods in terms of all the metrics. The metrics and solution methods are respectively considered criteria and alternatives. The average values of the metrics are

TABLE 7. Evaluation of mentioned methods in each metric measure

| Problem	MID		RAS		CPU Time	
	ε-constraint	LP-Metric	ε-constraint	LP-Metric	ε-constraint	LP-Metric
1	3.8467	3.4671	1.4076	1.9390	0.3229	0.2450
2	3.6648	3.4642	2.9087	4.9836	0.4029	1.5400
3	3.7217	3.4739	2.1986	3.7789	0.7600	9.3420
4	3.7527	3.5942	1.9349	3.5410	1.5114	37.7370
5	3.7562	3.6826	1.9077	3.3465	2.4443	57.7340
6	3.7456	3.7193	1.9839	3.7368	6.4350	45.0450
Average	3.7480	3.5669	2.0569	3.5543	1.9794	25.2738
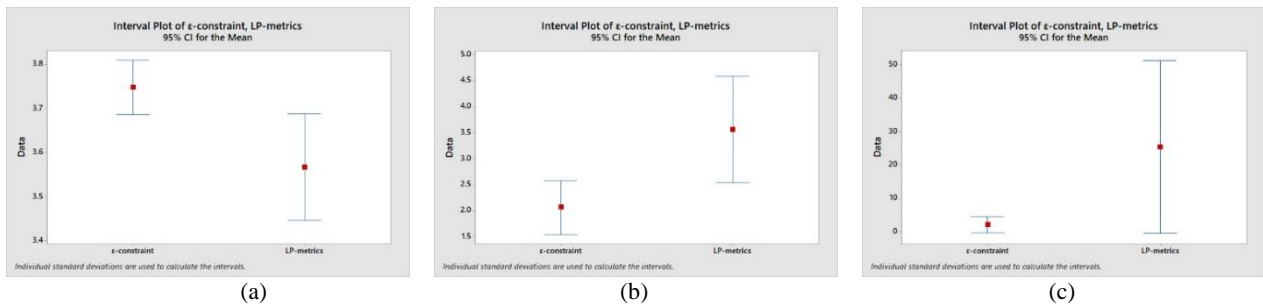
Figure 4. Intervals plots (at the 95% confidence level): (a) MID, (b) RAS, (c) CPU Time

utilized as the input to the proposed method in all the problems. TOPSIS developed as a compromise model by Hwang and Yoon [40], is commonly used in multi-criteria decision makings. The following steps explain the procedure of this method.

According to the results of TOPSIS shown in Table 8, the epsilon-constraint is determined as the superior method given its higher coefficient.

Procedure of the TOPSIS method

Step 1	$F_{ij} = \dfrac{f_{ij}}{\sqrt{\sum_{i=1}^{m} f_{ij}^2}}$, i=1,...,m, j=1,...,n.
	Normalized decision matrix with m rows (alternatives) and n columns (criteria)
Step 2	$v_{ij} = F_{ij} \times w_j$
	Weighted normalized decision matrix
	W_j: criteria weight, $\sum_{j=1}^{n} w_j = 1, w_j \geq 0,$
Step 3	$v_j^+ = \max_i v_{ij} ; \quad v_j^- = \min_i v_{ij}$, j=1,...,n.
	Assumption: "more is better" criteria.
Step 4	$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2} , d_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2}$ i=1,...,m
	Euclidean distance between each solution and the ideal and negative-ideal solution
Step 5	$C_i = \dfrac{d_i^-}{d_i^- + d_i^+}$
	The optimal solution having the largest C_i is the recommended solution.

TABLE 8. Results of TOPSIS

| Method	C_i	Rank
ε-constraint	0.943696	1
Lp-metrics	0.056304	2

9. DISCUSSION

In this section, a sensitivity analysis is performed to determine the accuracy and performance of the model in the case study. The performance of the proposed model was evaluated for the individual scenarios defined based on variations in the demand for fresh, processed, and reprocessed products. Table 9 presents these scenarios and the values of the objective functions obtained for the individual scenarios and determined using the epsilon-constraint method. Figure 6 shows variations in the values of the two objective functions for the individual scenarios.

According to Table 9 and Figure 5, an increase or decline in the demand does not improve or decline the values of the two objective functions, respectively, which validates the model results. These results can help with making decisions in cases of disruptive reductions or rises in demand. For instance, for fresh products, an up to 20% increase in demand would decrease the customer satisfaction, while it remains steady for an increasing demand for processed and reprocessed products.

TABLE 9. Sensitivity analysis of the demand parameters

Scenario	Change intervals of demands	d_{k_1}		d_{k_2}		d_{k_3}	
		Obj. 1	**Obj. 2**	**Obj. 1**	**Obj. 2**	**Obj. 1**	**Obj. 2**
1	-30%	0.88	12726.55	0.88	13524.85	0.88	14345.64
2	-20%	0.88	13405.47	0.88	13977.82	0.88	14465.85
3	-10%	0.88	14136.73	0.88	14431.05	0.88	14656.79
4	0%	0.88	14889.52	0.88	14889.52	0.88	14889.52
5	10%	0.86	14984.09	0.88	15364.07	0.88	15171.19
6	20%	0.85	14944.35	0.88	15838.71	0.88	15482.35
7	30%	0.85	15586.49	0.88	16319.26	0.88	15825.21
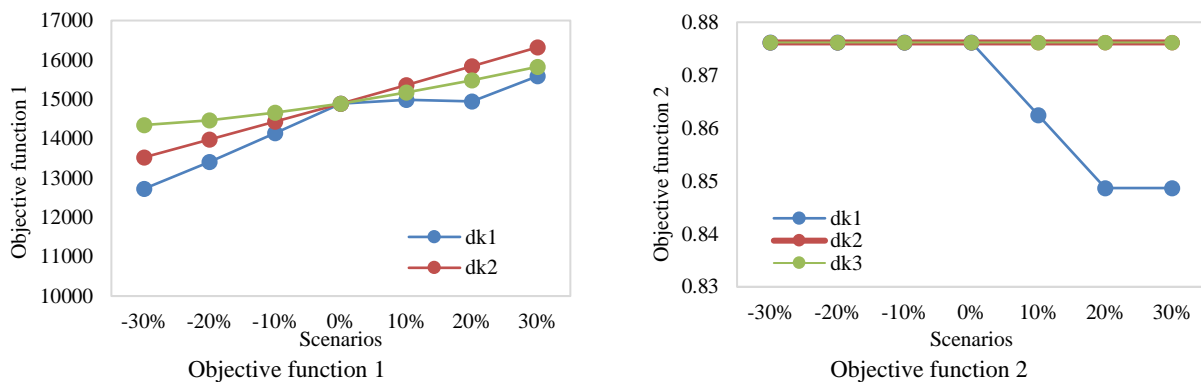
Figure 5. Sensitivity analysis of the demand parameters

10. CONCLUSION

This study proposed a novel bi-objective seven-echelon CLSC problem for the fish. The objectives comprised minimizing the total cost of the network and maximizing the responsiveness to customer demand in forward and reverse cases.

Lp-metrics and epsilon-constraint were employed to solve the proposed model. The present findings were validated by examining a real-world case in Iran. This model was applied to six test problems and the metrics were calculated by employing the solution methods. Using TOPSIS as a multi-criteria decision-making approach to determine the method with the higher performance in terms of all the metrics showed the satisfactory efficiency of epsilon-constraint.

It is recommended that further studies be conducted to include uncertainty of parameters and sustainability criteria in multi-period and multi-product problems. Other multi-objective optimization methods can also be used to solve the model. Given the significant increase in the burden of computation with an increase in the dimensions of the problem, heuristic and metaheuristic algorithms can be used in future research. Also, discussing the model complexity and some mathematical aspects of the model can be proposed for future research.

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Persian Abstract

چکیده

در سال‌های اخیر، بسیاری از صنایع در کشورهای پیشرفته به دلایل مختلف از جمله افزایش نگرانی‌های زیست محیطی، لجستیک معکوس را فرآیندی مهم در زنجیره تأمین خود دانسته‌اند. از آنجا که ماهی یک ماده غذایی فسادپذیر است، استفاده مجدد از محصولات بلااستفاده و ضایعات در هر سطح از زنجیره تامین یکی از دغدغه‌های اصلی تصمیم‌گیرندگان است. در این مقاله، یک مدل ریاضی جدید با هدف به حداقل رساندن هزینه‌های زنجیره تامین حلقه‌بسته ماهی و به حداکثر رساندن پاسخگویی به تقاضای مشتری ارائه شده است. به منظور حل مدل، از دو روش معیار جامع و اپسیلون محدودیت استفاده می‌شود. سپس براساس معیارهای عملکرد و با بکارگیری آزمون فرض آماری، روش‌های حل با یکدیگر مقایسه می‌شوند. سرانجام، از الگوریتم تاپسیس برای انتخاب روش برتر استفاده می‌گردد. به منظور اثبات کاربرد مدل، یک مطالعه موردی از یک زنجیره تامین حلقه بسته ماهی قزل آلا در شمال ایران با انجام تحلیل حساسیت تقاضا ارائه شده است. نتایج تجزیه و تحلیل نشان می‌دهد که مدل پیشنهادی و روش حل مورد تاییدند.