Optimizing a bi-objective multi-period fish closed-loop supply chain network design by three multi-objective meta-heuristic algorithms

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Abstract. Attention to a food supply chain has increased recently due to population growth and increased demand for food. Aquaculture development is advantageous as fish is a crucial constituent of the food basket of households. This study first presents a new bi-objective and multi-period mathematical model of a fish closed-loop supply chain (CLSC). The model is addressed by utilizing the multi-objective Keshtel algorithm (MOKA), NSGA-II, and MOSA. The Taguchi method is employed to tune these meta-heuristics to attain superior performance, and the ε-constraint method is used in solving small-sized problems to validate them. The results show that the exact method cannot solve large-sized problems. The solutions are compared in terms of different performance metrics. Using the 'filtering/displaced ideal solution' (F/DIS) method, NSGA-II and MOKA with a direct distance of 0.4228 and 0.8976 have the first and second performance ranks, respectively. Also, a case study including a trout CLSC in the north of Iran is investigated. The results and the case study show that the developed model can be applied to the proposed solution approach.

KEYWORDS: Closed-loop supply chain; Meta-heuristic algorithms; Reverse logistics; Bi-objective and multi-period model; Fish supply chain.

1. Introduction

Supply chain management (SCM) is an element that coordinates the flow of information, goods, and funds from origin to consumption zones [1]. From the perspective of operations research, supply chain network design (SCND) is a discipline that is employed for determining the ideal size and location of facilities and the flow of the facilities. Traditionally, most of the of supply chain (SC) processes were forward flows focusing merely on producing and distributing products to end-users [2, 3]. However, most of these processes are no longer in traditional; instead, they pay more attention to the environment through end-of-life (EOL) products. Considering the adverse socioeconomic and environmental effects of diverting waste to landfills at the EOL, closed-loop supply chain (CLSC) and reverse logistics (RL) are notions that inspire waste management [4, 5].

The environment has been under pressure with the increasing consumption rate of natural resources globally and the growing population [6, 7]. The food demand has tripled in the last 50 years, with human consumption 30 percent higher than the regeneration capacity of nature [8]. Recently, because of droughts and resulting water crisis and climatic change, suitable lands for cultivating crops have reduced, natural resources needed for animal husbandry have been destructed, and marine reserves have decreased in Iran, like other countries in the Middle East [9]. Therefore, it is required to modify the already available food SCs to meet the growing food demand [10, 11].

Seafood and the related products constitute a large amount of a consumption basket of the households in different regions. The situation of fish in the cold chain is represented in Figure 1 [12]. Hence, by expanding aquaculture farms, sustainable foods can be developed for the country, and its high effectiveness in preserving endangered species has been proven [13]. The Food and Agriculture Organization (FAO) in 2020 emphasized the impacts of optimization on fish farming because of the nearly equal rates of aquaculture and capture and the prediction that by 2030 the aquaculture production would additionally be amplified (Figure 2). According to the FAO and the Iranian Fisheries

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Organization reports, the production rate of cold-water fish in Iran has been growing. The most famous species of fish among all the many species is trout [14].

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The waste and losses of fish and seafood during production and processing is 20.2%, and the waste of retailers and consumers is 14.5% (Figure 3). With the global reduction in resources of aquaculture and increased costs of production, more attention should be paid to the processes and the waste in the aquaculture industry. In addition, because of considerable drops in natural resources, landfills, and product life, waste management has become a crucial issue. A dedicated recovery plan is needed to be allocated to separate EOL products considering their dissimilarity [15]. Therefore, it is vital to implement RL in the fish SC. Figure 4 indicates fish aquarium and fish waste in the fish market.

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To our best knowledge, this work is a pioneer study in the implementation of the RL in fish SCs in multi-period cases. There are specific SC strategies for every product. Since each product has unique characteristics, particular conditions are required for SCM of each product [16, 17]. Firstly, a network is presented for the fish CLSC. As a conventional method for fish waste recycling, the fish powder is produced to provide large amounts of organic fish food, maintain human health, and preserve the environment. Thus, fish waste recycling facilities are used in the present work for performing RL.

Moreover, we develop a new bi-objective mathematical model for minimizing the fish CLSC cost and maximizing customer demand responsiveness in reverse and forward SCs. SC decisions should be pursued by respecting economic issues and customer requirements considerations [18], since the primary objective of every industry is to reduce system costs and enhance customers' satisfaction [19, 20]. For model solving and studying the solution methods, we use some famous meta-heuristic algorithms. Besides, the Taguchi method is utilized to set the optimum parameters of the algorithms, and we consider a case study to show the algorithm's performance. It is based on the real data collected via related organizations and field research. Government agencies and private sector investors that seek to design their SC network optimally are the target customers of this optimization model.

This study is continued as follows. The review of the related literature and the mathematical model's details are presented in Sections 2 and 3, respectively. Section 4 offers solution approaches. The measures for evaluation of the algorithms' performance are explained in Section 5. A case study is conducted and studied in Section 6. The results of the computations are given in Section 7. The managerial insights of this paper are provided in Section 8. Conclusions and recommendations for further studies are provided in the last section.

2. Literature review

SCM is a strategic matter in companies looking to meet targets concerning time, economic competitiveness, and service quality, particularly in an economic atmosphere with trade globalization and accelerated industrial cycles [2]. For the construction of practical SCs, the expectation of industries from academic circles is to investigate innovative extensions and solve them effectively [21, 22]. The previous studies have used various research methods, including experiments, mathematical modeling, case study, and review, to work with vegetables, fruits, and dairies. Moreover, the literature review is a leading approach for meat products, while experiments have mainly been utilized regarding fish products, suggesting that further research can be carried out for fish [12]. As far as we know, no study exists on the fish RL issues in multi-period cases. Thus, the following literature review briefly describes the most related studies in perishable products SCs and RL.

The focus of the current work is on fish SCs by a review on cold SCs and perishable foods. Perishability has a significant effect on the design and management of food SCs [16].

Perishable products: Ghare and Schrader [23] initiated the studies on perishability and concluded that the inventory decay significantly influences the total inventory cost, if included in the inventory analysis. Besides, perishability has drawn the attention of practitioners and researchers in the SC field [24, 25].

Perishable Product Supply Chain (PPSC): Both academic and practical studies have increasingly paid attention to the perishability consideration in the SC. Diabat et al. [26] attempted to utilize integrated vehicle routing and inventory management in modeling an SC with perishable products. A meta-heuristic algorithm was introduced based on tabu search to address the mixed-integer linear programming (MILP) model. They stated that their algorithm needs a quicker computation in comparison with CPLEX software. Kamalabadi and Shaabani [27] considered an inventory-routing problem (IRP) that involves perishable products in two-level SCs. They proposed a population-based simulated annealing (PBSA) algorithm and compared its results with the genetic algorithms (GA) and simulated annealing (SA), indicating the superiority of the PBSA algorithm. As shown by the computational experiments, the PBSA algorithm has higher efficiency. A mathematical method was proposed by Vahdani et al. [28] for vehicle routing and production planning issues for the maximization of returns from the sale of perishable products. Location decisions were applied in the IRPs by Hiassat et al. [29] for finding the location of essential warehouses and classical decisions of IRPs. They proposed a GA for solving the model. An optimization model for the inclusive cold-chain-based low-carbon location-routing problem (LRP) was presented by Leng et al. [30] to minimize the total logistics costs and waiting time of a vehicle and client. In the cold chain logistics system, Song et al. [31] considered a vehicle routing problem (VRP). The objective is to minimize the total cost, including the energy consumption and the fixed cost. Review articles have also addressed managing the SCs of perishable products [12, 32].

Perishable Food Supply Chain (PFSC): Originally, Taylor used the term “perishable food supply chain” in his studies in 1994 [33]. Many studies have addressed the efficiency maximization of food SCs by presenting various approaches [24, 34]. Abedi and Zhu [35] presented an optimization model for fish culturing production procedure, spawn purchase, and distribution of harvested fish in a fish SC. They formulated a MILP model for the maximization of the total profit. According to the experimental results, farmers’ total profit would be elevated after applying the presented optimization strategy compared to the conventional farming strategy.

Soysal et al. [36] considered an IRP with environmental matters for food. They examined the advantages of horizontal collaboration associated with perishability, logistics costs, energy use (CO_2 emissions) from transportation procedures, and the IRP with several customers and suppliers. To this end, they developed a decision support model addressing these issues. Tabrizi et al. [16] developed a novel optimization method and investigated the equilibrium models in the perishable food SC as casework on the warm-water farmed fish SC. A bi-level optimization algorithm was developed to maximize the returns of farms and active stands in the fish distribution market.

Onggo et al. [37] studied the perishable IRP with stochastic demands and modeled it as mixed-integer programming. According to their tests, the algorithm improved the initial solution with reasonable computational times. A combined multi-product production planning and distribution allocation in the SC was proposed by Masruroh et al. [38] for a dairy manufacturer. According to the findings, the presented models had a significant role reducing of the total cost and growth of the annual gross profit. Chan et al. [39] developed a four-objective MILP model for an intelligent food logistics system. The formulated mathematical model was optimized by a revised multi-objective PSO algorithm using various social structures. Fasihi et al. [40] designed the fish CLSC. The proposed mathematical model is considered in a single period situation. The two exact methods, including the ε-constraint method and Lp-metric, were employed. Then, the performance metrics and a statistical hypothesis were used to compare the solution methods. Besides, various review studies have addressed perishable food SCs [41- 43]. The precise analysis described in Table 1 shows the gaps that highlight the distinction of this paper.

As a result of increasing public awareness and increasing attention from both industrial and academic circles, we recently witnessed significant contributions to RL/CLSC [44, 45]. Table 2 presents some review studies for providing more insight into the related studies.

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3. Mathematical modeling

3.1. Problem statement

The current study aims at designing a multi-period CLSC for fish logistic networks, which is a multi-period network, with producers (e.g., Pool-Farm, Rice-Farm, and Sea-Farm), distribution centers, processing and reprocessing centers (processed fish and fish powder centers), and customers (e.g., fresh fish markets, processed fish markets, and fish powder markets).

The forward flow is shown in Figure 5, in which goods are transferred to distribution centers and customers from producers and customers from distribution centers for meeting their unsupplied demand by producers. Moreover, it is assumed that there are fixed locations for customers and processing centers. Distribution and reprocessing centers and producer locations can have potential or fixed points of locations. The products returned in the reverse flow are transported to reprocessing centers for being transformed to byproducts. Then, they are transported again to the fish powder market's customers. Considering farms (i.e., producers) are regarded as the fish feed's potential customers, we can consider the network as a CLSC, in which producers have the role of fish powder customers.

Fish farms perform the harvesting process just only once a day. It is assumed that the demand for fresh fish is a priori; fish distribution centers can store a restricted amount of live fish in the aquariums to meet retailers' daily demand. The fish quality is decreased over time. Thus, it restricts the maximum number of periods for storing fish in fish stalls in the distribution centers. In the current work, a CLSC is designed for farmed fish in reverse and forward flow modes achieved by developing a bi-objective multi-period mathematical model. Therefore, it minimizes the chain cost and maximizes the customer demand responsiveness by gathering the fish waste and losses in the fish SC using a network.

{Please insert Figure 5 about here.}

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
$l_1 = 1, 2, ..., L_1$	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
$m = 1, 2, \ldots, M$	Fish processing center locations
$t = 1, 2, \ldots, T$	Time periods

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}	Transport cost per unit of live products from producer *i* to distribution center *j*
Cf_{ik_1}	Transport cost per unit of fresh products from producer *i* to customer k_1
Cf_{jk_1}	Transport cost per unit of fresh products from distribution center *j* to customer k_1
Cd_{im}	Transport cost per unit of fresh products from producer *i* to fish processing center *m*
Cd_{jm}	Transport cost per unit of fresh products from distribution center *j* fish processing center *m*
Cp_{mk_2}	Transport cost per unit of processed products from fish processing center *m* to customer k_2
Cr_{k_1l}	Transport cost per unit of waste products from customer k_1 to fish waste recycling center *l*
Cr_{ml}	Transport cost per unit of waste products fish processing center *m* to fish waste recycling center *l*
Cw_{lk_3}	Transport cost per unit of reprocessed products from fish waste recycling center *l* to fish powder markets k_3
Cq_{il}	Transport cost per unit of low-quality products from producer *i* to fish waste recycling center *l*
Cq_{jl}	Transport cost per unit of low-quality products from distribution center *j* fish waste recycling center *l*
Cq_{k_1l}	Transport cost per unit of low-quality products from customer k_1 fish waste recycling center *l*
Ch	Holding cost per unit of inventory from distribution centers for one period
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_1t}	Demand of fresh product by customer k_1 at time *t*
d_{k_2t}	Demand of the processed product by customer k_2 at time *t*
d_{k_3t}	Demand of the reprocessed product (fish powder) by fish powder markets k_3 at time *t*
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 customer k_1
β_{k_1}	Waste percentage of the product by 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 reprocessed product (fish powder)
φ'	Conversion rate of product to the processed product
MM	A big positive number
$\tau^{\max}$	Maximum consecutive periods that a live fish can be stored in a distribution center (aquarium)

Decision Variables

F_{ijt}	Amount of live products shipped from producer i to distribution center j at time t
F_{ik_1t}	Amount of fresh products shipped from producer i to customer k_1 at time t
F_{jk_1t}	Amount of fresh products shipped from distribution center j to customer k_1 at time t
R_{k_1lt}	Amount of waste products shipped from customer k_1 to fish waste recycling center l at time t
R_{mlt}	Amount of waste products shipped from fish processing center m to fish waste recycling center l at time t
D_{imt}	Amount of fresh products shipped from producer i to fish processing center m at time t
D_{jmt}	Amount of fresh products shipped from distribution center j to fish processing center m at time t
P_{mk_2t}	Amount of processed products shipped from fish processing center m to customer k_2 at time t
W_{lk_3t}	Amount of reprocessed products (fish powder) shipped from fish waste recycling centers l to fish powder markets k_3 at time t
Q_{ilt}	Amount of low-quality products shipped from producer i to fish waste recycling centers l at time t
Q_{jlt}	Amount of low-quality products shipped from distribution center j to fish waste recycling centers l at time t
Q_{k_1lt}	Amount of low-quality products shipped from the customer k_1 to fish waste recycling centers l at time t
Ih_{jt}	Amount of stored products by distribution center j at time t
λ_{it}	Amount of production by producer i at time t
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	1if fish waste recycling center l is opened at the location; 0, otherwise

3.3. Mathematical Model

The formulation of the bi-objective multi-period design of the fish CLSC is as follows:

$$\text{Min}\, Z = z_1 + z_2 + z_3 + z_4 \tag{1}$$

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

$$z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} Cf_{ij} \times F_{ijt} + \sum_{j=1}^{J}\sum_{k_1=1}^{K_1}\sum_{t=1}^{T} Cf_{jk_1} \times F_{jk_1t} + \sum_{i=1}^{I}\sum_{k_1=1}^{K_1}\sum_{t=1}^{T} Cf_{ik_1} \times F_{ik_1t}$$

$$+ \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{t=1}^{T} Cd_{im} \times D_{imt} + \sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{t=1}^{T} Cd_{jm} \times D_{jmt} + \sum_{m=1}^{M}\sum_{k_2=1}^{K_2}\sum_{t=1}^{T} Cp_{mk_2} \times P_{mk_2t}$$

$$+ \sum_{m=1}^{M}\sum_{l=1}^{L}\sum_{t=1}^{T} Cr_{ml} \times R_{mlt} + \sum_{k_1=1}^{K_1}\sum_{l=1}^{L}\sum_{t=1}^{T} Cr_{k_1l} \times R_{k_1lt} \tag{3}$$

$$+ \sum_{l=1}^{L}\sum_{k_3=1}^{K_3}\sum_{t=1}^{T} Cw_{lk_3} \times W_{lk_3t}$$

$$+ \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{T} Cq_{il} \times Q_{ilt} + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} Cq_{jl} \times Q_{jlt} + \sum_{k_1=1}^{K_1}\sum_{l=1}^{L}\sum_{t=1}^{T} Cq_{k_1l} \times Q_{k_1lt}$$

$$z_3 = \left(\sum_{j=1}^{J}\sum_{t=1}^{T} Ih_{jt} \times Ch \right) \tag{4}$$

$$z_4 = \sum_{m=1}^{M}\sum_{k_2=1}^{K}\sum_{t=1}^{T} P_{mk_2t} \times Cp + \sum_{l=1}^{L}\sum_{k_3=1}^{K_3}\sum_{t=1}^{T} W_{lk_3t} \times Cr + \sum_{i=1}^{I}\sum_{t=1}^{T} \lambda_{it} \times Cp' \tag{5}$$

$$\begin{aligned} \text{Max}\, Z' &= (\rho/2) \times \left(\Big(\sum_{i=1}^{I}\sum_{k_1=1}^{K_1}\sum_{t=1}^{T} F_{ik_1t} + \sum_{j=1}^{J}\sum_{k=1}^{K_1}\sum_{t=1}^{T} F_{jk_1t} \Big) / \sum_{k_1=1}^{K_1}\sum_{t=1}^{T} d_{k_1t} \right) \\ &+ (\rho/2) \times \left(\sum_{m=1}^{M}\sum_{k_2=1}^{K_2}\sum_{t=1}^{T} P_{mk_2t} / \sum_{k_2=1}^{K_2}\sum_{t=1}^{T} d_{k_2t} \right) \\ &+ (1-\rho) \times \left(\sum_{l=1}^{L}\sum_{k_3=1}^{K_3}\sum_{t=1}^{T} W_{lk_3t} \right) / \left(\sum_{k_3=1}^{K_3}\sum_{t=1}^{T} d_{k_3t} \right) \end{aligned} \tag{6}$$

The first objective function (Z) is given as the total costs, encompassing fixed opening costs, transportation costs, holding costs, production costs, and costs of the fish processing and waste recycling (reprocessing) centers (2)-(5). The maximum value of the second objective function (Z') is 1 comprising the reverse and forward responsiveness of the CLSC network. The denominator and numerator of the fraction indicate customer demand and the products transported to customers. For all the centers, the inventory is initially assumed as zero.

Subject to:

$$\lambda_{it} \times (1-\alpha_i) - \sum_{m=1}^{M} D_{imt} = \sum_{j=1}^{J} F_{ijt} + \sum_{k_1=1}^{K_1} F_{ik_1t} \qquad \forall\, i \in I, \forall t \in T \tag{7}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} F_{ijt} \le MM \times W_j \qquad \forall j \in J \tag{8}$$

$$\lambda_{it} \le \lambda c_i \qquad \forall\, i \in I, \forall t \in T \tag{9}$$

$$Ih_{j(t-1)} + \sum_{i=1}^{I} F_{ijt} = Ih_{jt} + \sum_{k_1=1}^{K_1} F_{jk_1t} + \sum_{m=1}^{M} D_{jmt} + \sum_{l=1}^{L} Q_{jlt} \qquad \forall j \in J, \forall t \in T \tag{10}$$

$$Ih_{j(t-1)} + \sum_{i=1}^{I} F_{ijt} \le \lambda h_j \qquad \forall j \in J, \forall t \in T \tag{11}$$

$$Ih_{j(t-1)} + \sum_{i=1}^{I} F_{ijt} \ge \theta \times \lambda h_j \qquad \forall j \in J_1, \forall t \in T \tag{12}$$

$$Ih_{jt} \le \sum_{t}^{t+\tau^{\max}} \sum_{k_1=1}^{K_1} F_{jk_1t} + \sum_{t}^{t+\tau^{\max}} \sum_{m=1}^{M} D_{jmt} + \sum_{t}^{t+\tau^{\max}} \sum_{l=1}^{L} Q_{jlt} \qquad \forall j \in J, \forall t \in T \tag{13}$$

$$\sum_{j=1}^{J} F_{jk_1t} + \sum_{i=1}^{I} F_{ik_1t} \le d_{k_1t} \qquad \forall k_1 \in K_1, \forall t \in T \tag{14}$$

$$\sum_{i=1}^{I} F_{ik_1t} \le \delta \times d_{k_1t} \qquad \forall k_1 \in K_1, \forall t \in T \tag{15}$$

$$\left(\sum_{i=1}^{I} D_{imt} + \sum_{j=1}^{J} D_{jmt} - \sum_{l=1}^{L} R_{mlt}\right) \times \varphi' = \sum_{k_2=1}^{K_2} P_{mk_2t} \qquad \forall m \in M, \forall t \in T \tag{16}$$

$$\sum_{k_2=1}^{K_2} P_{mk_2t} \le \lambda r_m \qquad \forall \mathrm{m} \in M, \forall t \in T \tag{17}$$

$$\sum_{m=1}^{M} P_{mk_2t} \le d_{k_2t} \qquad \forall k_2 \in K_2, \forall t \in T \tag{18}$$

$$\sum_{l=1}^{L} Q_{ilt} \le \alpha_i \times \lambda_{it} \qquad \forall i \in I, \forall t \in T \tag{19}$$

$$\sum_{i=1}^{I} \sum_{t=1}^{T} Q_{ilt} \le MM \times Y_l \qquad \forall l \in L \tag{20}$$

$$\sum_{l=1}^{L} Q_{jlt} \le \alpha_j \times Ih_{j(t-1)} \qquad \forall j \in J, \forall t \in T \tag{21}$$

$$\sum_{j=1}^{J} \sum_{t=1}^{T} Q_{jlt} \le MM \times Y_l \qquad \forall l \in L \tag{22}$$

$$\sum_{l=1}^{L} Q_{k_1lt} \le \alpha_{k_1} \times \left(\sum_{i=1}^{I} F_{ik_1t} + \sum_{j=1}^{J} F_{jk_1t}\right) \qquad \forall k_1 \in K_1, \forall t \in T \tag{23}$$

$$\sum_{k_1=1}^{K_1} \sum_{t=1}^{T} Q_{K_1lt} \le MM \times Y_l \qquad \forall l \in L \tag{24}$$

$$\sum_{l=1}^{L} R_{k_1lt} \le \beta_{k_1} \times \left(\sum_{i=1}^{I} F_{ik_1t} + \sum_{j=1}^{J} F_{jk_1t}\right) \times (1\text{-}\alpha_{k_1}) \qquad \forall k_1 \in K_1, \forall t \in T \tag{25}$$

$$\sum_{k_1=1}^{K_1}\sum_{t=1}^{T} R_{k_1lt} \le MM \times Y_l \qquad \forall l \in L \tag{26}$$

$$\sum_{l=1}^{L} R_{mlt} \le \beta_m \times (\sum_{i=1}^{I} D_{imt} + \sum_{j=1}^{J} D_{jmt}) \qquad \forall m \in M, \forall\ t \in T \tag{27}$$

$$\sum_{m=1}^{M}\sum_{t=1}^{T} R_{mlt} \le MM \times Y_l \qquad \forall l \in L \tag{28}$$

$$(\sum_{m=1}^{M} R_{mlt} + \sum_{k_1=1}^{K_1} R_{k_1lt} + \sum_{i=1}^{I} Q_{ilt} + \sum_{j=1}^{J} Q_{jlt} + \sum_{k_1=1}^{K_1} Q_{k_1lt}) \times \varphi = \sum_{k_3=1}^{K_3} W_{lk_3t} \qquad \forall\ l \in L,\ \forall\ t \in T \tag{29}$$

$$\sum_{k_3=1}^{K_3} W_{lk_3t} \le \lambda r_l \qquad \forall\ l \in L,\ \forall\ t \in T \tag{30}$$

$$\sum_{l=1}^{L} W_{lk_3t} \le d_{k_3t} \qquad \forall k_3 \in K_3,\ t \in T \tag{31}$$

$$\sum_{j=1}^{J}\sum_{t=1}^{T} F_{ijt} \le MM \times X_i \qquad \forall i \in I \tag{32}$$

$$\sum_{k_1=1}^{K_1}\sum_{t=1}^{T} F_{ik_1t} \le MM \times X_i \qquad \forall i \in I \tag{33}$$

$$\sum_{m=1}^{M}\sum_{t=1}^{T} D_{imt} \le MM \times X_i \qquad \forall i \in I \tag{34}$$

$$\sum_{l=1}^{L}\sum_{t=1}^{T} Q_{ilt} \le MM \times X_i \qquad \forall i \in I \tag{35}$$

$$X_i,\ Y_l, W_j \in \{0,1\} \qquad \forall i \in I, \forall l \in L, \forall\ j \in J \tag{36}$$

$$F_{ijt}, F_{ik_1t}, F_{jk_1t}, D_{imt}, D_{jmt}, D_{jmt}, R_{k_1lt}, R_{mlt}, W_{lk_3t}, Q_{ilt}, Q_{jlt}, Q_{k_1lt} \ge 0$$
$$\forall i \in I, j \in J, k_1 \in K_1, k_2 \in K_2, k_3 \in K_3, m \in M, l \in L, t \in T \tag{37}$$

$$Ih_{jt} \ge 0\ ,\ \lambda_{it} \ge 0 \qquad \forall i \in I\ ,\ \forall j \in J\ ,\ \forall t \in T \tag{38}$$

Constraint (7) states that the production level minus the depreciated product amounts and shipped to the processing centers is equivalent to the number of goods dispatched from the manufacturers to the customers and distribution centers. Given Constraint (8), only if a distribution center is open in a potential place, then a product is shipped there. Based on Constraint (9), the maximum amount of a producer's products the producer's production capacity) is equal to a predictable maximum production rate. According to Constraint (10), the inventory level of the previous period plus the number of goods taken from producers minus the sum of the goods transferred to the processing centers and customers and that of deteriorated products shipped to the reprocessing centers consists of the inventory level in each distribution in each period centers. According to Constraints (11) and (12), the inventory level of the previous period plus the number of goods received from the producers in a distribution center equal the holding capacity, and these constraints ensure using the minimum capacity of a distribution center. Constraint (13) ensures that the inventory level of a distribution center j is never higher than the total fish amount sent by the distribution center in the next $\tau^{\max}-1$ successive period.

According to Constraint (14), in each period, the demand for a fresh product is equivalent to the number of goods received from the distribution centers and producers. Constraint (15) imposes that the maximum customer demand for fresh fish is supplied directly by the producers. Constraint (16) state the total processed products dispatched to the processed product market. According to Constraints (17) and (18), the number of products shipped to the processed product market equals the anticipated maximum processing rate and the customer demand for the processed products.

Constraint (19) ensures that the waste production rate is equivalent to the amount of returned goods transferred to the reprocessing centers from the producers. According to Constraint (20), the returned goods are dispatched to a reprocessing center from a production center only if there is an open reprocessing center in the potential place for this facility. Like Constraints (19)-(20), Constraints (21)-(22), (23)-(24), (25)-(26), and (27)-(28) state that the facilities' maximum capacity is defined as a limit on the shipped products, and these constraints specify an opening facility as a prerequisite for transporting the products. Constraint (29) states that the total fish powder shipped to the fish powder market as the reprocessed good equals all the products returned from the manufacturers, processing centers, customers, and distribution centers, multiplied by the conversion rate. According to Constraints (30) and (31), the production capacity and demand of a fish powder market equal the amount of fish powder shipped to the fish powder market in each period. Constraints (32)-(35) ensure that the goods can be shipped to places, in which an open production center is present. Constraints (36)-(38) indicate non-negativity and binary constraints on the related decision variables.

4. Solution approach

A bi-objective multi-period model is developed in the present study, which considers a location problem (opening potential locations) by using some binary variables, leading to the model complexity [59, 60]. Besides, real-world problems are large, and the model will be NP-hard as the problem size increases [61]. Thus, because of the NP-hardness in the formulated model, exact techniques do not show efficiency, particularly for the problems with a larger size [62, 63]. In the present study, we use the multi-objective Keshtel algorithm (MOKA), NSGA-II, and MOSA for finding Pareto solutions. These algorithms are employed similar to the previous studies. Besides, the following sub-section explains encoding and decoding processes. This study uses commercially available software and evolutionary algorithms for small- and large-sized problems, respectively. The performance of the proposed meta-heuristics was verified using the ε-constraint method. Moreover, the performance of the ε-constraint method and evolutionary algorithms are compared by standard measuring metrics.

4.1 Encoding and decoding

The priority-based approach [64] is used in the current work. Recent studies have paid special attention to using this kind of encoding in contrast to edge-based encoding [65]. To develop and present our chromosome or array utilized in this work, we illustrate a small-sized example here to show that the proposed method satisfies all the constraints. It is assumed that the numbers of producers equal 3, distribution centers equal 2, fresh products customers equal 3, customers of processed products equal 2, processing centers equal 1, reprocessing centers equal 2, and the number of customers reprocessed is 2.

The presented chromosome is a matrix possessing ($3i+4j+4k_1+k_2+k_3+2m+2l$) columns and 30 rows (i.e., the number of periods). Each row is correspondent to one time period (T), and the columns are divided into six parts. Figure 5 indicates the flows used for designing these parts. Also, Figure 6 shows the schematic view of the proposed chromosome generated randomly in the interval [0, 1]. The digits will be transformed into the priority-based matrix after sorting the values. Parts and sub-parts soring are separately performed.

{Please insert Figure 6 about here.}

As observed in Part 1, the quantity of goods dispatched to customers and distribution centers of fresh products ($j+k_1$) from producers (i) is shown. Part 1 is indicated following sorting in Figure 7 as a chromosome element, which is offered only in period one to better understand the point. Likewise, Figure 8 demonstrates the priority-based chromosome and random key of Part 2 in period one. The amount of products transported to customers of fresh products (k_1) from distribution centers (j) is presented in this part. Also, the model's inventory control mechanism is related to this part. It is necessary to save the inventory amount of each period in another matrix and use it in the subsequent period.

{Please insert Figure 7 about here.}
{Please insert Figure 8 about here.}

Figure 9 shows the third part's priority-based chromosome and random key in period one. This part's sequence comprises the data related to the amounts of products transported to the processing centers (m) from distribution centers and producers ($i+j$). Figure 10 presents Part 4. Using the sequence of this part encompasses the data associated with the amounts of returned goods transported to the reprocessing centers (l) from distribution centers, producers, processing centers and customers ($i+j+m+2k_1$). Figure 11 represents part five. The sequence of this part includes the data on the amounts of processed goods transported to the customers of processed fish (k_2) from processing centers (m). Figure 12 presents Part 6. The sequence of this part includes the data related to the amounts of reprocessed products (fish powder) transported to fish powder customers (k_3) from reprocessing centers (l). Figures 13-16 present allocation procedures of Parts 1 to 6.

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{Please insert Figure 10 about here.}
{Please insert Figure 11 about here.}
{Please insert Figure 12 about here.}
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4.2 MOKA

To study one of the recent and efficient algorithms, we utilize a recent meta-heuristic algorithm, called MOKA [66]. Hajiaghaei-Keshteli and Aminnayeri [67, 68] offered the single-objective KA as a population-based algorithm, inspired by the fantastic feeding behavior of Keshtels, which is a kind of duck. The algorithm begins with a primary population, named Keshtels, and search in the feasible area using swarm intelligence. In this algorithm, Keshtel's greedy feeding behavior searches the feasible space prudently and logically. Figure 17 depicts the pseudo-code of the MOKA.

{Please insert Figure 17 about here.}

4.3 MOSA

Another algorithm (i.e., MOSA) is compared in this paper with other solution approaches. Initially, Kirkpatrick et al. [69] proposed SA for solving larger combinatorial optimization problems. Here again, three mutation operators (i.e., swap, reversion, and uniform mutations) are utilized to escape from local optima. Eq. (39) presents the accepting mechanism used in this research, where x' presents the newly produced solution and x denotes an initial solution. Figure 18 indicates the pseudo-code of this algorithm.

(39)

$$\Delta f_j = f_j(x') - f_j(x) \qquad j = 1, 2, \ldots, n$$

{Please insert Figure 18 about here.}

4.4 NSGA-II

The present work utilizes the NSGA-II proposed by Deb et al. [70] to evaluate the quality of solutions. A binary tournament selection strategy is used by the NSGA-II. To escape from local optima, the algorithm utilizes the uniform mutation operator, and also a uniform crossover operator is employed to do the diversification phase. Figure 19 depicts the pseudo-code of the NSGA-II.

{Please insert Figure 19 about here.}

5. Performance measures for comparison of the algorithms

Five performance metrics are utilized for evaluating the performance of the proposed multi-objective meta-heuristics. These measures are explained in the following:

a) Number of Pareto solutions (NPS): It gives the number of Pareto-optimal solutions calculated for each algorithm. The algorithm shows a better performance if the NPS in an algorithm is larger.

b) Mean ideal distance (MID): This distance given in Eq. (40) is used for calculating the distance between the Pareto solutions and the ideal point [71]. The performance of the method is greater if the values of this index are lower.

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

c) Spread of non-dominance solution (SNS): It is employed for measuring the variety of Pareto archive solutions, given as Eq. (41) [71]:

$$SNS = \sqrt{\frac{\sum_{i=1}^{n}(M - C_i)^2}{n-1}} \tag{41}$$

where, $C_i = \sqrt{f1_i^2 + f2_i^2}$ and $M = \frac{\sum_{i=1}^{n}\sqrt{f1_i^2 + f2_i^2}}{n}$

d) Maximum spread (MS): This measure is used for measuring the extension of Pareto solutions, which is calculated as Eq. (42) [62].

$$MS = \sqrt{\sum_{i=1}^{I}(minf_i - maxf_i)^2} \tag{42}$$

e) CPU time: the running speed of a method is evaluated by this index.

6. Parameter tuning and setting

In the present section, we set the algorithm and model parameters tuned in the following subsections.

6.1 Setting the model parameters

We generate and test six problems for examining the performance of the solution techniques and proposed model. They are classified by numbers of reprocessing centers (*L*), producers (*I*), customers (K_1), processing centers (M), processed products customers (K_2), distribution centers (*J*), and the fish powder (K_3). Table 3 shows the values of these parameters. We solve each problem 30 times to evaluate the algorithms.

As the first problem, the case study is implemented in Iran's Northern region to indicate the applicability of the solution algorithms and research model. For testing the proposed model, different conditions and parameters are taken in using solution methods. The data ware gathered in Mazandaran, Iran. The main cities of the province are shown in Figure 20. The cost of the transportation is defined between the northern cities of Iran by their distances in km, transport manner (i.e., fresh or processed fish: 0.18, fish powder: 0.09 \$/ton.km, live fish: 1.36), and fare rates (i.e., \$ per km). The values of other parameters of the model are given in Table 4.

{Please insert Table 3 about here.}
{Please insert Table 4 about here.}
{Please insert Figure 20 about here.}

6.2 Tuning the algorithm parameters

In the present work, the Taguchi method [72] is used for setting the parameter values that lead to the best algorithm performance. The method is designed to maximize the controllable factor effects and minimization of the noise effect. For this purpose, the signal-to-noise ratio (SNR) is employed. As in this research, the proposed response is minimization type, "the smaller is better" is used to adjust the parameters of each algorithm. The nominated SNR value in the present work is presented in Eq. (43).

$$S/N = -10\log\left(\frac{S\left(Y^2\right)}{n}\right) \tag{43}$$

where *n* represents the number of orthogonal arrays and *Y* denotes the response value. Besides, Eq. (44) represents the selected response. There are two core notions (i.e., diversity and convergence) linked to this response. The MID calculates the algorithm's convergence rate, and the MS presents the diversity of Pareto solutions.

$$MCOV = \frac{MID}{MS} \tag{44}$$

The first phase for creating the Taguchi design is identifying the factor levels. Table 5 presents this phase, in which each factor has three levels ($x=i+j+k_1+k_2+k_3+m+l$). Minitab ® software is used in the second phase. The L_9 and L_{27} designs are chosen for MOSA, NSGA-II, and MOKA.

{Please insert Table 5 about here.}

Likewise, Figures 21-23 show the effect plot of the SNR for each algorithm. Table 6 shows the appropriate parameter levels for the problem one. Using a similar approach, the suitable levels of parameters are determined in other algorithms. Similarly, for all test problems, the tuned values are for the first test problem.

{Please insert Figure 21 about here.}
{Please insert Figure 22 about here.}
{Please insert Figure 23 about here.}

{Please insert Table 6 about here.}

7. Computational results and discussion

To study and investigate the performance of the employed algorithms, we probe these algorithms by six test problems, and the results are compared. Likewise, the algorithms solve these test problems on a PC with Intel ® Core ™ i7-8750H CPU @ 2.20GHz. Moreover, using the measures presented in Section 5, these meta-heuristics are evaluated by conducting a one-to-one comparison (Table 7). Also, the 'ε-constraint' that validates these algorithms shows that large-sized problems cannot be solved by such a method, as shown in Table 7. Furthermore, considerable CPU time is taken to solve the small-sized problem, which indicates the NP-hardness of the problem, especially in large-sized problems.

The obtained higher MS, SNS, and NPS, and lower MID and CPU time metrics show superior performance. The analysis of variance (ANOVA) method is utilized for comparing the obtained measures. As proved by the results, the performances of the algorithms showed a statistically significant difference. Figures 24-28 represent the intervals plot (95% confidence level) of the six points listed in Table 7 for the individually mentioned algorithms for each measure. It is clear that the best performance is attributed to the NSGA-II in terms of the NPS, MS, and SNS measures. Besides, the MOSA and MOKA algorithms showed the highest performance concerning CPU time and MID, respectively.

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{Please insert Figure 27 about here.}
{Please insert Figure 28 about here.}
{Please insert Table 7 about here.}

Considering the variety of the above-mentioned standard measure indicators, the 'filtering/displaced ideal solution' (F/DIS) method is employed to find the best algorithm [73]. As such, the direct distance value for each algorithm is computed by Eq. (45). A smaller value of a direct distance indicates a better algorithm with less distance from the ideal solution. These values are presented in Table 8.

$$\text{Direct distance} = \sum_i \left| M_i^N \right|$$

Wherein;

$$M_i^N = \frac{M_i - M_i^*}{M_i^*} \tag{45}$$

M_i : Average of six problems per each metric.

M_i^* : Ideal solution, which is the best value of each metric among all algorithms.

M_i^N : Normalized values of M_i .

The NSGA-II is selected as the best algorithm with the smallest distance from the ideal point considering the direct distance measure. As a second choice, the MOKA shows good performance as well.

{Please insert Table 8 about here.}

8. Managerial insights

This section presents the managerial insights that are driven by this study. The proposed model considers the environmental considerations by designing a closed-loop fish SC network for collection and recycling of low-quality products and waste from different levels of SC (fish farms, distribution centers, fish markets and processing centers). Managers and investors in the aquaculture industry can apply the suggested model to enhance their decision-making from tactical and strategical aspects. Iran has a tremendous potential capacity in aquaculture through the availability of appropriate natural resources, industrial equipment, and human resources, including academic experts. Realizing this potential for domestic and international supply could enhance Iran's economy and preserve marine resources.

The model considers potential locations for the production, distribution, and recycling centers. The optimization results of this model could assist investors and governors in identifying the best locations for an optimal distribution and transportation network of fish products while enriching their business through the recycling of fish wastes. The results significantly impact the understanding of requirements for opening new facilities in different defined levels of fish industry, considering the trade-off between customer satisfaction and total cost. Managers continuously look for efficient ways for problem solving and successful decision-making. The managers of fish farms and fish powder factories could use this model to reduce their fixed opening and transportation costs and better manage production flows and SC by fitting the production capacities and market demands with the model constraints. This study provides several meta-heuristics that the managers of fish industries can use to optimize their network design.

9. Conclusion

A new bi-objective multi-period seven-echelon CLSC problem was proposed in the present work for the fish SC. The objectives included minimizing the network total cost and maximizing the customer demand responsiveness in reverse and forward cases. In this work, the model was expanded to a multi-period condition, in which the inventory was considered, which brings it closer to the real-world condition with more complexity. A number of well-known meta-heuristics were used for solving the proposed model. A real-world case was studied in Iran for verification of the research findings. Moreover, the Taguchi method was employed for tuning the parameters of all algorithms so that the best results could be obtained. We solved the model for six problems by three proposed algorithms, and the metrics were calculated. Then, the results were analyzed via the ANOVA method, which indicated a significant difference in performance among applied approaches. The results show that the NSGA-II was more efficient in terms of criteria related to the number and variety of solutions. Also, the MOSA worked better if solution time would be a priority, while the MOKA performed better if proximity to the ideal point was important. As a result, the NSGA-II is found as the best algorithm, followed by the MOKA. The values of the parameters are tuned according to the topology of the studied area, which may not apply to other regions.

To enhance the model, the operational conditions (e.g., fish production scheduling) and optimum rates of the market supply need to be studied. Since the type of product flows (namely, live fish, fresh fish, and fish powder) could be different between every two levels, the multi-mode transportation options could be applied in later research. The impact of biological factors (e.g., weight and growth rate) on the optimization of the fish farming industry and pricing policy can be considered in further research. Besides, further studies are recommended to include sustainability criteria and uncertainty of parameters in multi-product problems. Considering more factors (e.g., fish disease and climate change) could increase the uncertainty of the model parameters. The impact of the COVID-19 on the aquaculture sector and fish SC can be considered for future research. Also, the model could be improved by using fuzzy modeling, stochastic programming, and robust programming. It is also possible to use other multi-objective optimization algorithms, hybrid meta-heuristics or some heuristics to solve the model. Also, it is recommended that future studies discuss the model complexity and its mathematical dimensions.

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List of Figure Captions

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[1] FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ca9229en.
[2] www.statista.com.

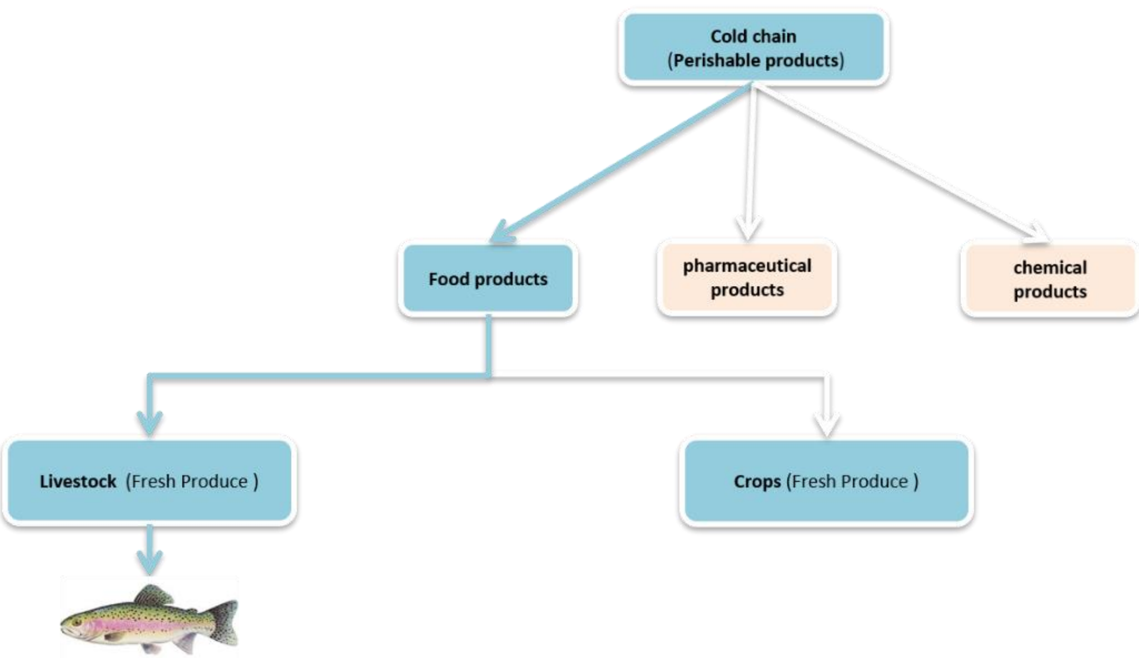
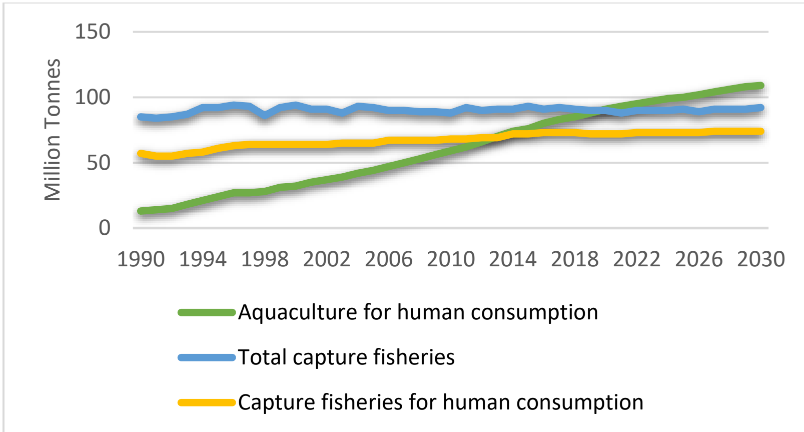
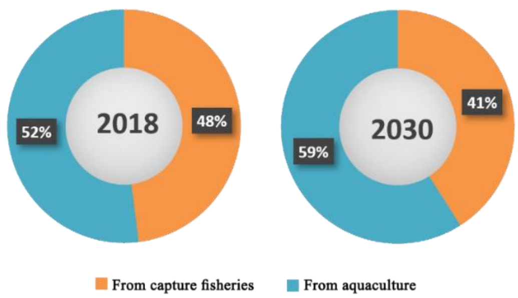


Figure 1. Fish situation in the cold chain.



(a) Production of global capture fisheries and aquaculture, 1990-2030.



(b) Increasing role of aquaculture in terms of global food fish consumption.

Figure 2. Fisheries and aquaculture.[3]

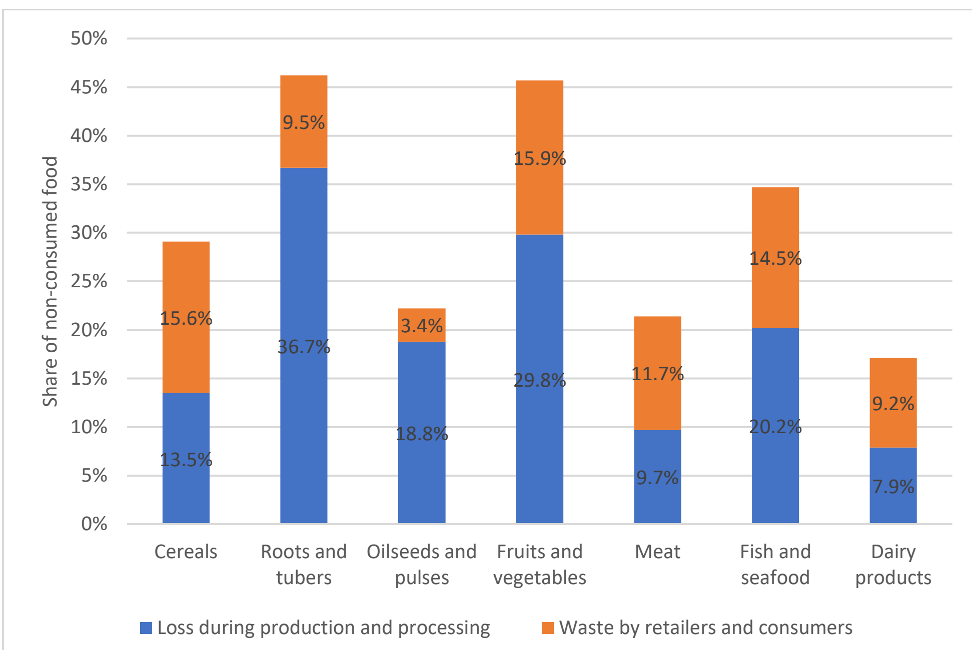


Figure 3. Share of food loss and waste worldwide, by type.[4]

[3] FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome. https://doi.org/10.4060/ca9229en.
[4] www.statista.com.

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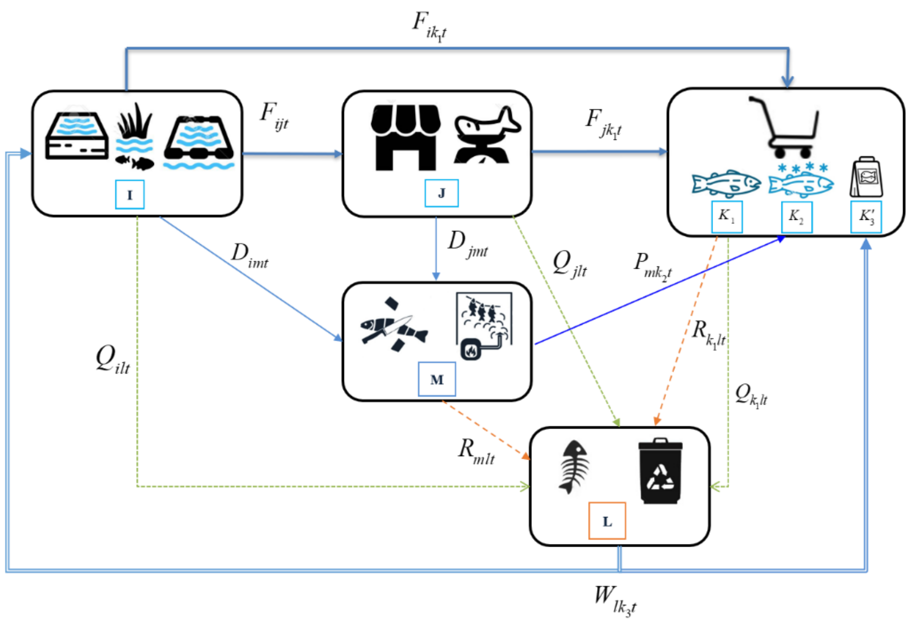

Figure 5. Fish CLSC flowchart.

Part		Part 1		Part 2		Part 3		Part 4		Part 5		Part 6	
Levels (number of columns)		i	$j+k_1$	j	k_1	$i+j$	m	$i+j+m+2k_1$	l	m	k_2	l	k_3
Period	1												
	…												
	T												

Figure 6. Schematic view of the proposed chromosome.

Levels (number of columns)	i			$j+k_1$				
Random key	0.276	0.680	0.655	0.163	0.119	0.498	0.960	0.340
Priority	3	1	2	4	5	2	1	3

Figure 7. First part's priority-based chromosome and random key in period one.

Levels (number of columns)	j		k_1		
Random key	0.585	0.223	0.751	0.255	0.505
Priority	1	2	1	3	2

Figure 8. Second part's priority-based chromosome and random key in period one.

Levels (number of columns)	i+j					m
Random key	0.699	0.890	0.959	0.547	0.138	0.149
Priority	3	2	1	1	3	2

Figure 9. Third part's priority-based chromosome and random key in period one.

Levels (No. of columns)	i+j+m+2k_1												l	
Random key	0.258	0.841	0.214	0.812	0.244	0.929	0.350	0.197	0.151	0.616	0.473	0.352	0.831	0.585
Priority	8	2	10	3	9	1	7	11	12	4	5	6	1	2

Figure 10. Fourth part's priority-based chromosome and random key in period one.

Levels (No. of columns)	m	k_2	
Random key	0.549	0.917	0.285
Priority	1	1	2

Figure 11. Fifth part's priority-based chromosome and random key in period one.

Levels (No. of columns)	l		k_3		
Random key	0.757	0.253	0.380	0.567	0.075
Priority	1	2	2	1	3

Figure 12. Sixth part's priority-based chromosome and random key in period one.

$for\ t = 1\ to\ T$

Inputs: *I: set of source*

J: set of applicant

D_j*: demand of applicant j*

Ca_i*: capacity of source i*

V(I+J): Encode solution of period t

Outputs: $Xaloc_{ij}$*: amount of shipment between nodes*

X_i *and* Y_j*: binary variable shows the opened applicant*

While $\sum_i Ca_i \geq 0$

Step1: $Xaloc_{ij} = 0\ \forall i \in I, \forall j \in J$

Step2: select value of the first column of sub-segment I for i index

select value of the first column of sub-segment J for j index

Step3: $Xaloc_{ij} = \min(Ca_i, D_j)$

Update demands and capacities

$Ca_i = Ca_i - Xaloc_{ij}$ $D_j = D_j - Xaloc_{ij}$

Step4: if $Ca_i = 0$ *then* $V(1,I)=0$

if $D_j = 0$ *then* $V(1,J)=0$

End while

Step5: for $j = 1$ *to* J

if $\sum_j Xaloc_{ij} > 0$ *then* $Y_j=1$

End for

for $i = 1$ *to* I

if $\sum_i Xaloc_{ij} > 0$ *then* $X_i=1$

End for

End for

Figure 13. Procedure of priority-based for Part 1.

for $t = 1$ *to* T

Inputs: *I: set of source*

J: set of applicant

D_j*: demand of applicant j*

Ca_i*: capacity of source i*

V(I+J): Encode solution of period t

INV_{it-1}*= amount of saved goods in storage i at period t-1*

Outputs: $Xaloc_{ij}$*: amount of shipment between nodes*

INV_{it}*: amount of remained goods in storage i at period t*

$Ca_i = Ca_i + INV_{it-1}$

While $\sum_j D_j \geq 0$ *or* $\sum_i Ca_i \geq 0$

Step1: $Xaloc_{ij} = 0 \ \forall i \in I, \forall j \in J$

Step2: select value of the first column of sub-segment I for i index

select value of the first column of sub-segment J for j index

Step3: $Xaloc_{ij}=\min(Ca_i, D_j)$

Update demands and capacities

$Ca_i = Ca_i - Xaloc_{ij}$ $\quad D_j = D_j - Xaloc_{ij}$

Step4: if $Ca_i=0$ *then* $V(1,I)=0$

if $D_j=0$ *then* $V(1,J)=0$

End while

Step5: $INV_{it} = Ca_i$

End for

Figure 14. Procedure of priority-based for Parts 2 and 3.

for $t = 1$ *to* T

Inputs: *I: set of source*

J: set of applicant

D_j*: demand of applicant j*

Ca_i*: capacity of source i*

V(I+J): Encode solution of period t

Outputs: $Xaloc_{ij}$*: amount of shipment between nodes*

Y_j*: binary variable shows the opened applicant*

While $\sum_j D_j \geq 0$

Step1: $Xaloc_{ij} = 0 \ \forall i \in I, \forall j \in J$

Step2: select value of the first column of sub-segment I for i index

select value of the first column of sub-segment J for j index

Step3: $Xaloc_{ij}=\min(Ca_i, D_j)$

Update demands and capacities

$Ca_i = Ca_i - Xaloc_{ij}$ $\quad D_j = D_j - Xaloc_{ij}$

Step4: if Ca_i=0 then V(1,I)=0
if D_j =0 then V(1,J)=0
End while
Step5: for j= 1 to J
if $\sum_j Xaloc_{ij} > 0$ *then Y_j=1*
End for
End for

Figure 15. Procedure of priority-based for Part 4.

for $t = 1$ *to* T
Inputs: I: set of source
J: set of applicant
D_j: demand of applicant j
Ca_i: capacity of source i
V(I+J): Encode solution of period t
Outputs: $Xaloc_{ij}$: amount of shipment between nodes
While $\sum_i Ca_i \geq 0$
Step1: $Xaloc_{ij} = 0 \ \forall i \in I, \forall j \in J$
Step2: select value of the first column of sub-segment I for i index
select value of the first column of sub-segment J for j index
Step3: $Xaloc_{ij}$=min (Ca_i , D_j)
Update demands and capacities
$Ca_i = Ca_i - Xaloc_{ij}$ $D_j = D_j - Xaloc_{ij}$
Step4: if Ca_i=0 then V(1,I)=0
if D_j =0 then V(1,J)=0
End while
End for

Figure 16. Procedure of priority-based for Parts 5 and 6.

1. Land the (*M*) Keshtels and calculate their fitness
2. Do non-dominate sorting and calculate crowding distance
3. Sort Keshtels respect to the crowding distance
4. Find the Lucky Keshtels (LK).
5. Find the best lucky Keshtel.
6. For each LK (M_1)
   6.1. Swirl the Nearest Keshtel (NK) around the LK.
   6.2. If NK finds better food than LK, replace NK with LK, find new NK, go to Step 6.1
   6.3. If the food still exists, attract the NK, go to Step 6.1, if not, go to Step 8.
7. Let the LKs remain in the lake.
8. Startle the Keshtels which have found less food and land new ones. (M_3)
9. Move the remained Keshtels in the lake between other Keshtels. (M_2)
10. Merged populations [M; M_1; M_2; M_3]
11. Do non-dominate sorting and Calculate crowding distance
12. Sort Keshtels respect to the crowding distance
13. Select (N) better Keshtels from these merged populations for the next iteration
14. Do again Steps 11 and 12 for this new population
15. If stopping criteria are satisfied, stop, if not, go to Step 5.

Figure 17. MOKA Pseudo-code.

1. Parameter setting
2. Initialize and evaluation fitness functions (x, $f_j(x)$)
3. Best solution = (x, $f_j(x)$)
4. For 1 to max-iteration
   4.1. Do mutation operator (x')
   4.2. Calculate the fitness function and (Δf_j)
      4.3.1. If $\Delta f_1 \leq 0 \ \&\&\Delta f_2 \geq 0$
         Update the Best solution = (x', $f_j(x')$)
         Update the solution $x=x'$
      4.3.2. Else if $\Delta f_1 \geq 0 \ \&\&\Delta f_2 \geq 0 \ ||\Delta f_1 \leq 0 \ \&\&\Delta f_2 \leq 0$
         Put this solution in Pareto set
      4.3.3. Else $\Delta f_1 \geq 0 \ \&\&\Delta f_2 \leq 0$
         $P_1 = \exp\left(\frac{-\Delta f_1}{T}\right)$, $P_2 = \exp\left(\frac{-\Delta f_2}{T}\right)$, h=rand
         If $h < P_1$ && $h < P_2$
         Update the solution $x=x'$
5. Update temperature ($T=\alpha * T$)
6. Do non-dominate sorting in this Pareto set.
7. If stopping criteria are satisfied, stop, if not, go to step 4.1.

Figure 18. Pseudo-code of the MOSA.

1. Initialize *Population*;
2. Generate random *population*;
3. Evaluate Objectives Values;
4. **For** *each Parent and Child Population* **do**
5. Assign Rank (level) based on Pareto;
6. Generate sets of *non-dominated solutions*;
7. Determine *the crowding distance*
8. Loop (inside) by adding solutions to the next generation
9. **End**
10. Determine the population front;
11. **For** each determined front
12. Roulette wheel selection (NSGA-II);
13. Generate a new population with *mutation* and *crossover*
14. **End**

Figure 19. Pseudo code of the NSGA-II.

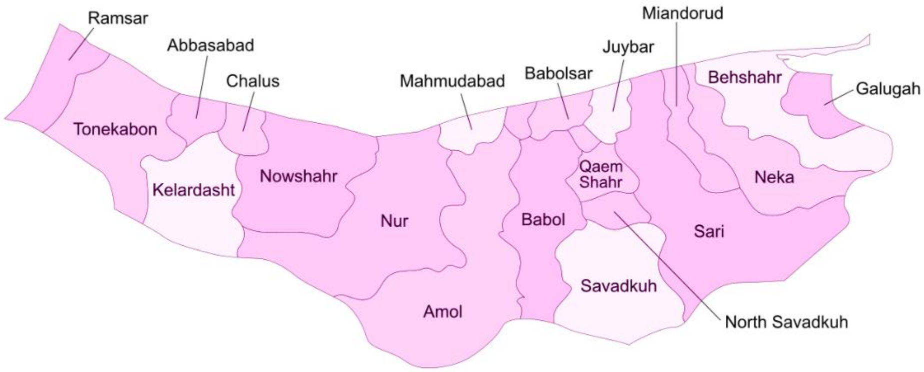

Figure 20. Main cities of Mazandaran province.

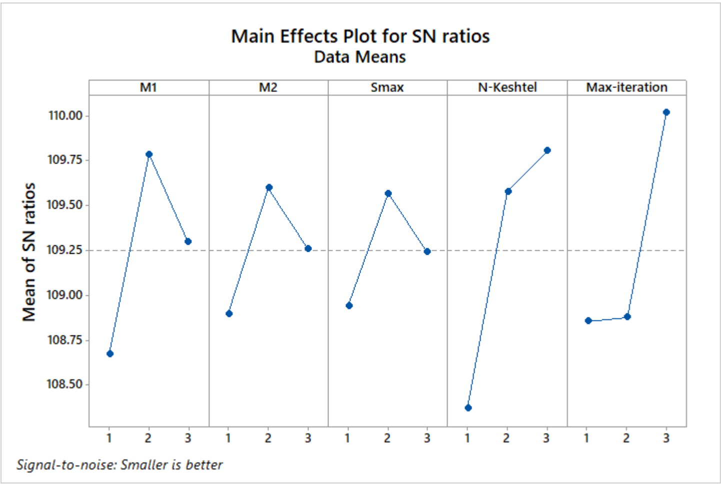

Figure 21. SNR plot for the MOKA.

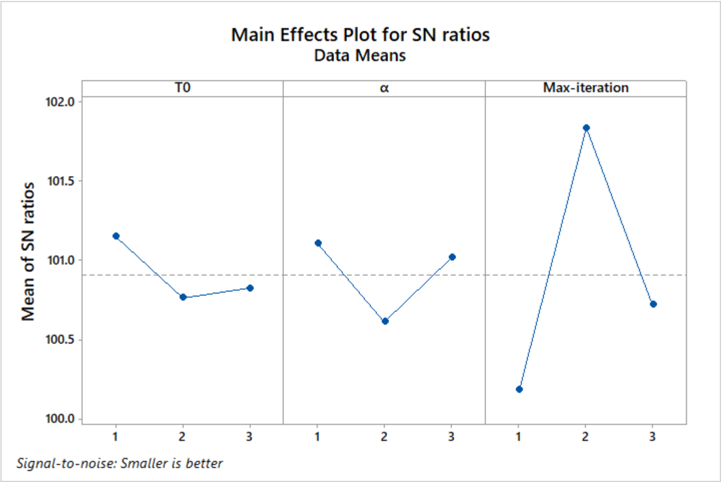

Figure 22. SNR plot for the MOSA.

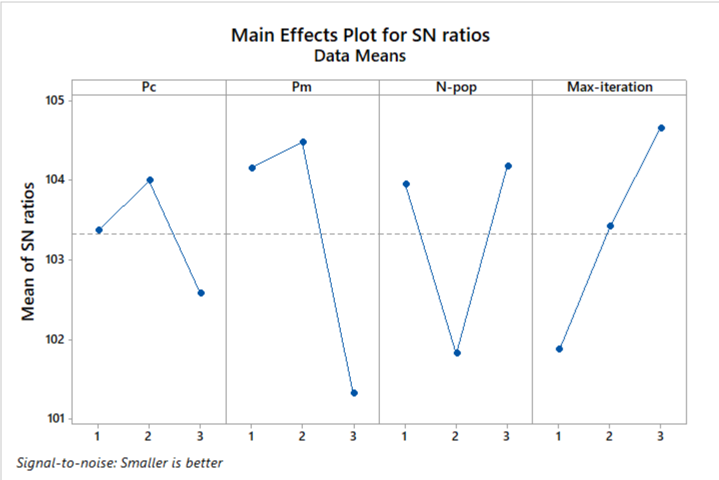

Figure 23. SNR plot for the NSGA-II.

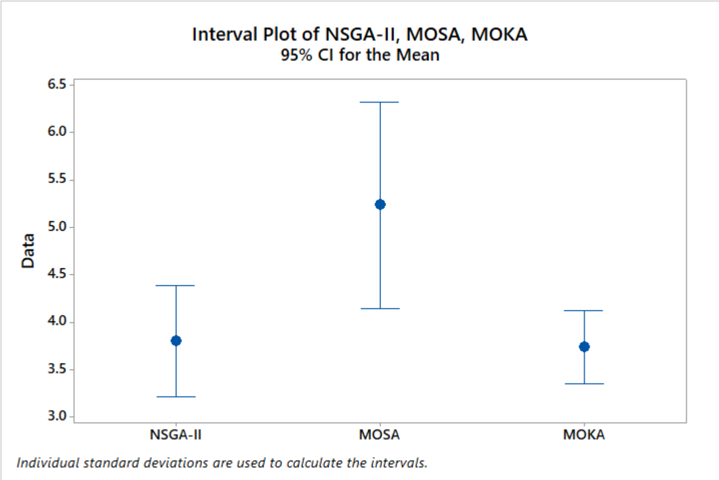

Figure 24. MID intervals plot (95% confidence level).

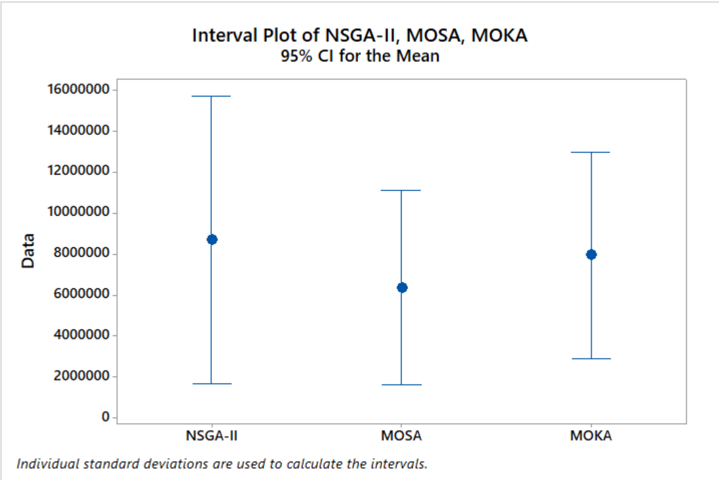

Figure 25. MS intervals plot (95% confidence level).

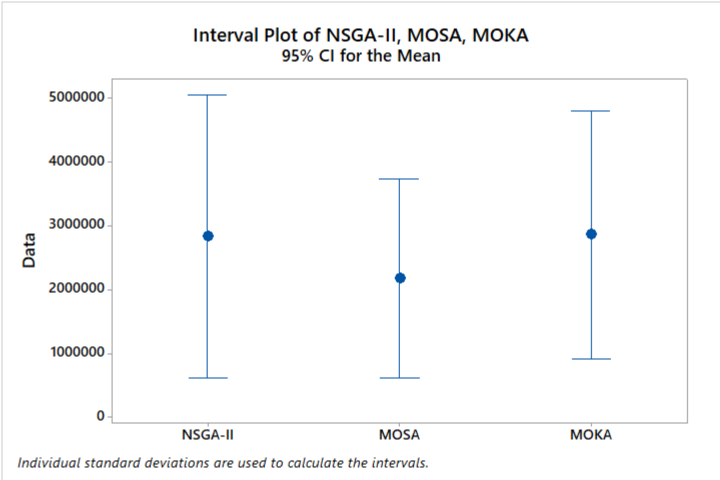

Figure 26. SNS intervals plot (95% confidence level).

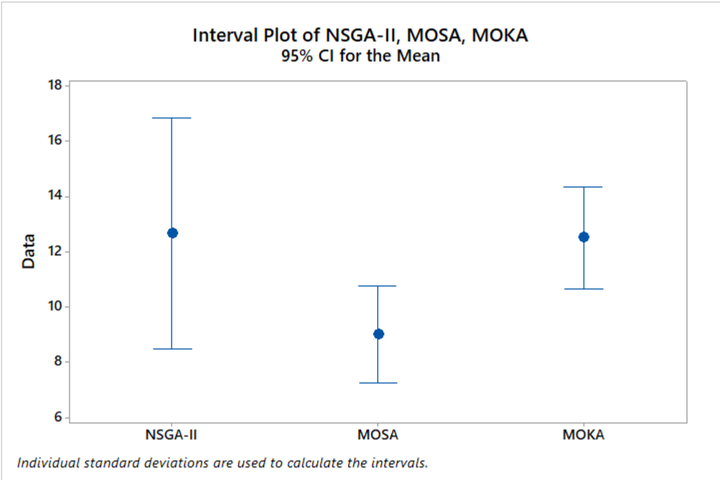

Figure 27. NPS intervals plot (95% confidence level).

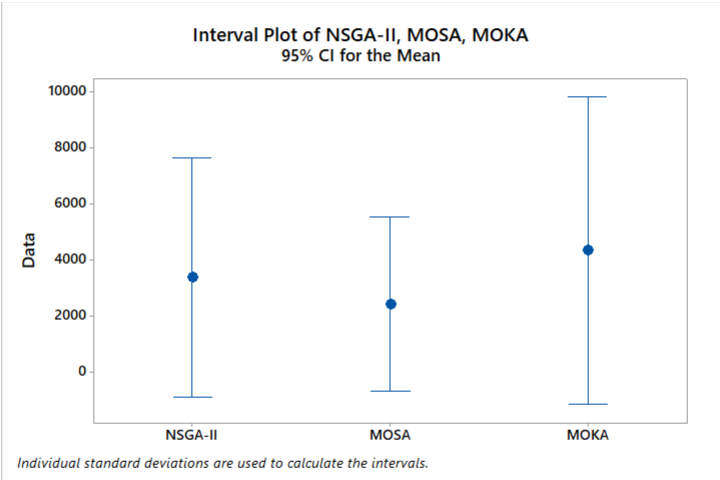

Figure 28. CPU time intervals plot (95% confidence level).

List of Table Captions

Table 1. Comparison of previous studies with the current research.

Type	Author(s)	Objective function	Modeling	Period	Solution approach	Example	Network structure
Perishable Product Supply Chain	(Diabat et al., 2016) [26]	SO- Transportation cost	Fixed Route linear programming (FRLP)	M	EX, MHE	Numerical	-
	(Shaabani and Kamalabadi, 2016) [27]	SO - Total cost	Lagrangian lower bound program (LLBP)	M	EX, MHE	Numerical	-
	(Vahdani et al., 2017) [28]	SO - Total profit	Mathematical programming (MP)	M	HE, MHE	Numerical	-
	(Hiassat et al., 2017) [29]	SO- Total cost	Mixed integer programming (MLP)	M	MHE	Numerical	-
	(Leng et al., 2020) [30]	MO- Total cost, Waiting time of clients and vehicles	Non- Linear Programming (NLP)	S	MHE	Numerical	-
	(Song et al., 2020) [31]	SO- Total cost	NLP	S	HE, MHE	Numerical	-
Perishable Food Supply Chain	(Abedi and Zhu, 2017) [35]	SO- Total profit	MILP	M	EX	Case (farmed Trout-USA)	-
	(Soysal et al., 2018) [36]	SO- Total cost	Chance-constrained programming model	M	EX	Case (fig and cherry-The Netherland)	-
	(Tabrizi et al., 2018) [16]	BL- Total profit	NLP	M	MHE	Case (Warm-water farmed fish- Iran)	-
	(Onggo et al., 2019) [37]	SO - Total cost	Mixed-integer programming (MIP)	M	HE, MHE	Numerical (Agricultural Produce)	-
	(Masruroh et al., 2020) [38]	SO- Total profit, total setup costs	MILP	M	EX	Numerical (Dairy)	-
	(Chan et al., 2020) [39]	MO- Transport cost, food quality, CO_2 emission, total weighted delivery lead time	MILP	M	MHE	Numerical (Food)	-
	(Fasihi et al., 2021) [40]	MO- Total cost, Responsiveness to customers' demand	MILP	S	EX	Case (farmed Trout-Iran)	CLSC
This study		MO- Total cost, Responsiveness to customers' demand	MILP	M	EX, MHE	Case (farmed Trout-Iran)	CLSC

Objective function: SO = Single-objective optimization, MO = Multi-objective optimization, BL = Bi-level optimization
Period: S = Single, M = Multi
Solution approach: EX = Exact solution method, HE = Heuristics method, MHE=Meta-heuristic method
Network structure: RL= Reverse logistics, CLSC= Closed-loop supply chain

Table 2. Reviews related to the CLSC and RL.

Paper	Area	Scope	Time scope
Van Engeland et al. [46]	RL	RL and waste management	1995-2017
Govindan and Bouzon [47]	RL and CLSC	RL barriers and drivers	2004-2015
Coenen et al. [48]	CLSC	Complexity and uncertainty in CLSC	2012- 2017
Kazemi al. [3]	RL and CLSC	The whole scope in CLSC and RL	2000 -2017
Barz et al. [49]	CLSC	The bullwhip effect in CLSC	2004-2018
Gaur and Mani [50]	CLSC	Strategic issues and competition	1992-2015
Islam and Huda [51]	CLSC	WEEE	1999-2017
Larsen et al. [52]	RL and CLSC	Financial performance	1995-2016
Prajapati et al. [53]	RL	The scope area in RL	1997-2017
Shekarian [54]	CLSC	CLSC models via GT	2004-2018
Bensalem and Kin [55]	RL and CLSC	The whole scope in CLSC and RL	1995-2017
De Giovanni and Zaccour [56]	CLSC	Return functions/Coordination mechanisms	2011-2018
Manavalan and Jayakrishna [57]	CLSC	ERP/ IoT/ Industry 4.0	2009-2018
Raza [44]	RL and CLSC	The whole area in CLSC and RL	2008-2019
Peng et al. [58]	CLSC	Uncertainty factors, methods, and solutions of CLSC	2004-2018

Table 3. Proposed 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

Table 4. Setting of other model parameters.

Parameter	Values	Unit
T	30	Period (day)
$\tau^{\max}$	2	day
f_i	Uniform ~ [81.9, 4670]	Dollar ($)
f_j	Uniform ~ [1458.3, 11340]	Dollar ($)
f_l	Uniform ~ [2083.2, 5950]	Dollar ($)
d_{k_1t}	Uniform ~ [0.99, 11]	Ton
d_{k_2t}	Uniform ~ [0.66, 2]	Ton
d_{k_3t}	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,		Percentage

β_m =0.4, θ=0.5, δ=0.2, ρ=0.6, φ=0.25, φ'=1.2	
Cp =2273, Cr =454, Cp' =909, Ch =10	Dollar per Ton

Table 5. Ranges of algorithm parameters along with their levels.

Algorithm	Factor	levels		
		1	2	3
MOKA	M_1	0.05	0.1	0.15
	M_2	0.2	0.25	0.3
	S_{max}	10	15	20
	N-Keshtel	50	100	150
	Max-iteration	2x	3x	4x
MOSA	T_0	30	40	50
	α	0.99	0.9	0.88
	Max-iteration	4x	8x	12x
NSGA-II	*Pc*	0.7	0.8	0.9
	Pm	0.05	0.1	0.15
	N-pop	50	100	150
	Max-iteration	2x	3x	4x

Table 6. Optimal value of parameters.

Algorithm	Optimal value
MOKA	M_1 =10%; M_2=25%; S_{max} =15; *N-Keshtel*=150; *Max-iteration*=4x.
MOSA	T_0 =30; α=0.99; *Max-iteration*=8x.
NSGA-II	*Pc*=0.8; *Pm*=0.1; *N-pop*=150; *Max-iteration*=4x.

Table 7. Assessment of the algorithms in metrics.

Problem	MID				MS			
	MOKA	MOSA	NSGA-II	ε-constraint	MOKA	MOSA	NSGA-II	ε-constraint
1	3.4063	5.9034	3.4940	3.8598	965390	614560	527160	344250
2	3.9139	4.0005	3.5172	3.6662	5004900	4153500	4966700	2154600
3	3.5900	5.5372	3.6732	3.7229	6373400	4579000	7726900	2645400
4	3.3021	4.2516	4.6142	NA	9626100	7455800	6650200	NA
5	4.2686	6.7541	4.3479	NA	11117000	7232100	12241000	NA
6	3.9218	4.9695	3.1382	NA	14426000	14010000	19920000	NA
Mean (M_i)	**3.7338**	5.2361	3.7975	NA	7918798	6340827	**8671993**	NA
Best (M_i^*)	**3.7338**				**8671993**			

Problem	SNS				NPS			
	MOKA	MOSA	NSGA-II	ε-constraint	MOKA	MOSA	NSGA-II	ε-constraint
1	336960	230870	163240	119240	13	7	13	10
2	1739400	1549000	1509800	726650	11	9	16	10
3	2244100	1577600	2046900	897740	13	8	12	10
4	3502000	2460900	2503900	NA	15	9	7	NA
5	3539900	2471000	5451800	NA	13	9	10	NA
6	5743400	4704000	5242800	NA	10	12	18	NA
Mean (M_i)	**2850960**	2165561.667	2819740	NA	12.50	9.00	**12.67**	NA
Best (M_i^*)	**2850960**				**12.67**			

Problem	CPU Time			
	MOKA	MOSA	NSGA-II	ε-constraint
1	63.0882	27.0378	43.5609	1502.17

2	361.0080	152.4256	248.6944	8022.43
3	1275.0613	637.5322	796.9125	31876.52
4	2351.7762	1447.2491	2050.2325	NA
5	11628.0947	7038.9003	8262.8371	NA
6	10320.2267	5160.6324	8772.1053	NA
Mean (M_i)	4333.2092	**2410.6296**	3362.3905	NA
Best (M_i^*)	**2410.6296**			

Table 8. Results of the F/DIS method.

Metrics	Algorithms		
	MOKA	**MOSA**	**NSGA-II**
MID	0.0000	0.4023	0.0171
MS	0.0869	0.2688	0.0000
SNS	0.0000	0.2404	0.0110
NPS	0.0132	0.2895	0.0000
CPU Time	0.7975	0.0000	0.3948
Direct distance	0.8976	1.2010	**0.4228**

Biography:

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