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Bi-Objective Fuzzy Food Bank Network Design with Considering Freshness of Food Baskets

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Abstract

This paper deals with the modeling of the Food Bank (FB) network in the conditions of uncertainty in the demand of charities and the capacity of donating food. The importance of creating a FB network, along with providing quality food, led to consider the two objective functions of minimizing the costs of the total FB network and maximizing the minimum freshness of the food basket. The simultaneous optimization of the above two objective functions is aimed at making correct routing-inventory and allocation decisions. In this paper, food items in food baskets with high shelf-life and low shelf-life are considered. The results of solving the sample problems by combining the operators of two Genetic Algorithm (GA) and Salp Swarm Algorithm (SSA) showed that with the increase in the freshness of the food baskets, the costs of the FB network have increased. Also, the sensitivity analysis showed that the increase in uncertainty in the network leads to an increase in the cost of FB network and a decrease in the freshness of the food basket. The comparison of the results between the algorithms also showed that the efficiency of HGSSA is much higher than GA and SSA and the problem solving time by these methods is extremely lower. The use of HGSSA has increased the rate of achieving effective solutions by 14.06%.

Keywords: Food bank network, Shelf-life, Routing-inventory-allocation, HGSSA.

1 | Introduction

Food insecurity has become a growing problem among low-income groups in affluent countries [1]. The increasing trend of poverty, taking into account the problem of food wastage in developed countries in parallel, causes aggravation of concern [2]. Because the global food system produces large amounts of waste during the food packaging process and in the food itself [3]. The waste of produced food for human consumption in all around the world, can be estimated at one third (approximately 1300 million tons) annually [4]. The problem that food retailers and final consumers throw away usable nutrients is more visible, especially in developed countries [5]. Food is wasted in various ways, including raw and cooked or pre-cooked, as well as food that is thrown away in the production, distribution, service and sales processes [6].

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FBs can be considered as a solution to reduce the problem of food waste [7], [8]. They can be defined as non-profit and voluntary organizations with the aim of recovering and redistributing surplus food and preventing its waste [9]. In addition to reducing waste, the FB helps to maintain and preserve the health of the environment, it also recovers the perishable food and delivers it to the needy people [10], [11]. In this way, food that can be consumed but cannot be sold will be available to people in need. In other words, FBs as a bridge between food surplus on the one hand and human needs on the other hand, create a well-driven chain between them. In fact, the role of FBs is to value part of the food waste that is safe and nutritious for human consumption and during the Supply Chain Network (SCN), should not be thrown away and sent directly to the landfill as waste [12], [13]. The different areas of FBs activities include programs in order to identify companies which can help with donations to provide surplus food sources and financial aids, and they also include holding campaigns to attract volunteers and collect food. FBs mostly distribute food to charities that are in direct contact with people in need and are not themselves responsible for the final distribution of food [14].

In 2014, in the United States, it was concluded that 55% of FB customers were dissatisfied with not receiving fresh fruits and vegetables, and 47.1% of them were dissatisfied with not receiving protein materials such as meat and dairy products. This observation showed that customers are more welcoming and supportive of Food Bank (FB) that is client focused and takes into account the required nutrition and nutritional value. Recently Feeding America in several initiatives, has adopted the policy of moving towards this type of FB that focuses on nutrition and health [15]. Today, the trustees of FBs do not only think about providing food and ending the problem of hunger. They also consider the importance of the healthy life of low-income households. This new approach has caused FBs to focus on the quality of the food they distribute in addition to its quantity. Therefore, the food distributed among the needy also targets their health. In this regard, it is very important that the FBs that provide food to the low-income groups, while paying attention to meeting the basic nutritional needs, also pay attention to improving the level of health and protecting them against obesity and chronic diseases [16].

This paper is compiled in six parts. In Section 1, an introduction to FB and its importance was discussed. In Section 2, the literature review of FB research is discussed. In this section, specific research gaps and research innovations are stated. In Section 3, the modeling of the bi-objective FB problem is discussed and the fuzzy programming method is used to control the uncertainty parameters of demand and supply. In Section 4, HGSSA algorithm is introduced and its operators are examined. Also, the initial solution is described in this section. In Section 5, the results of calculations are shown. In Section 6, the conclusion of the research is discussed and future research is identified.

2 | Literature Review

Delpish et al. [17] designed a preliminary study to address cognitive bias through a visual analysis approach in the decision-making process. They developed interactive dashboards as an alternative to the traditional spreadsheet format using specific FB data. A preliminary study was conducted to evaluate the effectiveness of the dashboard and the results showed that the dashboards reduced the amount of confirmation bias. Young [18] studied a sequential resource allocation problem faced by food distribution in a non-profit organization. He [18] formulated an SRA model that can be used to design an optimal visit route. It focuses on maximizing equity and reducing waste.

An experiment is designed to evaluate and analyze the performance of the algorithm and the proposed method provides better solutions in terms of waste reduction. In addition, the model is extended to consider the travel cost to find an approximately optimal visiting path. A larger-scale case study is also performed, which shows that the algorithm obtains high-quality solutions in terms of parity and efficiency. Crama et al. [19] developed solution methods to solve the inventory routing problem for a perishable product under uncertainty. The computational study shows that under certain conditions, a simple ordering policy can achieve very good performance, but using more advanced solution methods, significant statistical and economic improvements are achieved.

Ghahremani-Nahr et al.| J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540

Huang et al. [20] design a perishable food SCN with inflation and time value of money. They used discounted cash flow method to measure the profit under inflation. It is observed that demand rate is affected by the food's price and the quality at the time of purchase and also food's quality deteriorates over time, which results in a decreasing demand rate. Martins et al. [21] propose a Mixed-Integer Linear Programming (MILP) model to study the problem of redesigning a multi-echelon FB SCN. Their proposed model considers all dimensions of sustainability - economic, environmental and social - through three objective functions. The results show that attributing the highest priority to the environmental objective leads to the most balanced solutions. A survey of Vancouver FB members was conducted by Holmes et al. [22] to assess demographic characteristics, Household Food Insecurity (HFI) and FB use. Fisher's exact tests were used to study the association between member characteristics and severe HFI. The results of the survey showed that FBs were used on average twice per month by members that 54 percent of it belongs to long-term users and 66 percent were reported as severe HFI. Onggo et al. [23] designed an agri-food SCN with one supplier and several retailers. This is an inventory routing problem known as the Perishable Inventory Routing Problem (PIRP) with random demands. They model it using a MILP and propose a simulation algorithm that integrates Monte Carlo simulation into an iterative local search to solve it. Experiments show that the proposed algorithm can improve the initial solution with reasonable computation times. For perishable products Dai et al. [24] proposed three different cyclic inventory-routing problems. They assumed the demand for perishable products to be dependent on price and inventory and verified its efficiency by presenting a hybrid heuristic algorithm. In order to check the effect of the parameters on the optimal solution, a sensitivity analysis was performed. For an inventory routing problem, a dynamic and stochastic approach was proposed by Violi et al. [25]. In the presented approach products with a high perishability must be delivered from a supplier to a set of customers. They used a rolling horizon approach which is based on a multistage stochastic linear program, to manage all the features of the problem effectively. The effectiveness of the proposed approach was confirmed by performing some computational experiments on medium-sized samples that their data was collected from an agri-food company in southern Italy.

Alkaabneh et al. [26] developed a framework for optimizing resource allocation by FBs. They formulated a Markov Decision Process model of the problem and approximated the value function using a policy iteration scheme. Computational experiments using real-world data were used to evaluate the performance of the algorithm. The algorithm demonstrated a 7.73% improvement in total utility. In a study decision support model for aggregators is presented by Mandal et al. [27], which is able to reduce food waste by allocating donated food items from retailers to FBs and also maximize the profitability of the collector and minimize the environmental impact. They investigated how the availability of different types of vehicles affects the aggregator's profit. The results of the investigations showed that the aggregator could possibly be applied and generate managerial insight. In a study about food industry, in order to consider resiliency and uncertainty in a multi-period, multi-product SCN design simultaneously, Arabsheybani and Arshadi Khasmeh [28], developed a robust bi-objective multi-product mathematical model. For making coordination between production planning, supplier selection, distribution, and order allocation in a flavor plant, they presented an approach in which, the constraint method is used for obtaining Pareto solutions. A real case was applied in Iran, and then a sensitivity analysis was performed to trace the trade-off between optimization and robustness. A multi-objective mathematical programming model was developed by Orjuela et al. [29] in order to optimize the cost, energy consumption and the traffic congestion. They modeled the uncertainty of product lifetime as a Weibull random variable, and assumed food perishability as a decision variable, affected by the use of car refrigerators. The results identified road congestion and uncertain perishability of products as critical factors for SCN performance and design.

In order to design the non-profit FB's SCN, Kaviyani-Charati et al. [30] presented a mathematical model that takes into account cold and conventional facilities and fleets to deal with all kinds of food, considering the sustainability factors in the multi-objective model. Considering many uncertain parameters and time constraints, they conducted a real case study in the city of Tehran. The results of the surveys indicate that in order to reduce food waste and transportation costs, the use of a heterogeneous fleet is very effective and necessary. To promote health in food-insecure communities and to use the learning experiences of nursing students in this direction, Jin et al. [31] conducted a case study examining a partnership between a public university and a regional FB. The results showed that the participation of the nursing program with FBs during epidemics can play a central role in improving the health of the community. Sosenko et al. [32] created a set of data containing information on the number of FBs and the volume of parcels in the Trussell Trust network, from 2011 to 2019, through 325 local authorities and created an information panel. They predicted the number of food parcels distributed by FBs using a quasi-experimental approach. The results of their investigations showed that since 2011, the responsibility of using the FB in Britain has been on the structure of its welfare system, and it is also possible to reduce severe food insecurity by making changes and reforms in the benefits system, that have been proven to play a role in increasing the use of FBs. Li and Song [33] presented a model to explore the dynamic impacts of external uncertainties on food SCN. They found that the impacts of external uncertainty elements were significantly different, the combination of different external uncertainty elements aggravated or reduced the risks of food SCN. And some uncertainty elements had both positive and negative impacts in the whole sample period, as the magnitude and direction of the impacts of various uncertainties in different periods had time-varying characteristics. Perdana et al. [34] presented the data as a support for designing a food SCN strategy during covid-19 pandemic using an integrated agent-based modelling and robust optimization (RO). They proposed an integrated model with an Agent-Based Framework (ABM) and robust RO to investigate and develop the food SCN under normal and epidemic conditions. In order to optimize the proposed model, the required additional data collected from the reports of government agencies were used. Orjuela-Castro et al. [35] presented big challenges of modeling in perishable food SCN such as delivery times, specific biophysical conditions of food, food losses and etc. They proposed a multi-objective, multi-echelon and multi-product, MOLP to design perishable food logistics networks, which is solved through e-constrains method, in AMPL. Finally, it is applied in a case study which is about the perishable fruit SCN. Abbas et al. [36] in a study in order to find the estimated results for increasing the food SCN robustness, used logistics regression and simulation technique. In this regard, the advanced SCN of China one belt one road was selected for delivering foods to the end consumers. The results show that, using this robust SCN has advantages such as; increasing the performance of the food SCN, timely and fast delivery of food with the ability to track it, reducing vulnerability ratio and reducing the possibility of fraud activities.

Kayikci et al. [37] in a study, presented a dynamic pricing model that uses real-time IoT sensor data at different stages to make pricing decisions. After evaluation the effect of the sale price, rate of discount, amount of replenishment, and freshness score on profit and food waste, it was concluded that there is huge potential for using hyperspectral imaging sensors in a retailer's FSC. A bi-objective optimization model was developed by Abbasian et al. [38], in order to integrate the location, routing and inventory problems which arise in designing a resilient sustainable perishable food SCN. They considered the route disruptions and traffic conditions effects on the deterioration of products. Then in order to solve the mixed-integer nonlinear bi-objective optimization model, a novel hybrid method was developed by using the Heuristic Multi-Choice Goal Programming and Utility Function Genetics Algorithm. Krishnan et al. [39] presented a multi objective MILP model to optimize the perishable FSC network. They modelled economic, environmental and social dimensions of sustainability and waste recovery plant for valorizing food waste. This model was applied to the real case study about processed mango fruit SCN. RO approach is used to capture the impact of supply uncertainty. In order to simultaneously minimize costs and carbon dioxide emissions, Akbarzadeh Sarabi et al. [40] presented a new multi-objective decision support model that is able to design a sustainable multi-product green SCN for perishable food products. The results showed that the total amount of carbon emissions is more due to the amount of carbon produced in warehouses than transportation activities. Gómez-Pantoja et al. [41] introduce an optimization model for the FB Resource Allocation Problem, which takes into account inventory management, purchases, product-beneficiary compatibilities, balanced nutrition, and priority of beneficiaries. They also propose an adaptive heuristic to solve large instances of this problem. The mathematical formulation and the proposed heuristic are evaluated. Computational results reveal that our heuristic is able to produce good quality solutions in short computation times.

Table 1 shows the research gap of the current paper in the field of FB.

Table 1. Research gap in the field of FB.

Ref.	Objective Function															
	Time	Distance	Cost	Co2 Emission	Social Impact	Freshness	Food Value	Routing	Allocation	Inventory	Location	Uncertainty Control Method	Solution Method	Multi-Product	Multi-Echelon	Multi-Period
Orgut et al. [42]	*							*	*				E			
Cuevas Ortuño and Gómez Padilla [43]			*						*	*		F	E		*	
Bocewicz et al. [44]	*							*		*	*		Si	*		*
Aras and Bilge [45]			*				*		*		*	R	E	*		*
Schneider and Nurre [46]		*						*					H			
Martins et al. [21]				*			*		*		*		H	*	*	*
Li et al. [47]			*							*			H		*	
Castañón et al. [48]			*						*				E		*	
Marthak [49]			*					*	*		*		E	*		*
Burgess and Sunmola [50]		*										F	M			
Solina and Mirabelli [51]			*							*			E			*
Güner and Utku [52]			*					*		*			E		*	*
Kazancoglu et al. [53]				*									E		*	*
Taghikhah et al. [54]				*						*			E		*	*
Gholami-Zanjani et al. [55]			*							*	*	S	E	*	*	*
Kothamasu et al. [56]				*						*	*	S	E		*	
Krishnan et al. [39]				*	*	*			*		*	R	E		*	
Akbarzadeh Sarabi et al. [40]				*	*	*			*		*		E		*	
Kaviyani-Charati et al. [30]				*	*	*			*	*	*	S	E-M	*	*	*
Sosenko et al. [32]				*					*	*			E			
Perdana et al. [34]				*				*		*		R	E		*	
Orjuela-Castro et al. [35]			*	*					*		*		E	*	*	
Present paper			*	*				*	*	*		F	E-M	*	*	*

Exact = E, Fuzzy = F, Meta-Heuristics = M, Heuristics = H, Robust = S, Stochastic = S, Simulation = Si.

According to the *Table 1*, it can be seen that the topic of freshness of food has not been seen in the FB network so far and the importance of this concept has been neglected. Also, the development of a hybrid algorithm in solving optimization problems is of interest to researchers today, and in this paper, the HGSSA is used. In this paper, the distribution of cold and hot food together with each other to charities is considered and the perishability of these foods affects their freshness. Hence, the designed FB includes a combination of routing-inventory and allocation problems.

The importance of the FB has led to the modeling of the FB problem under uncertain demand and supply in this paper. The model presented in this paper simultaneously reduces the design costs of the routing-allocation-inventory network and maximizes the minimum freshness of food basket distributed to charities. Therefore, a network including financial donors, food donors, FBs and charities is considered. The designed model tries to consider the freshness of the food basket along with the costs of transportation, inventory and routing. For this, HGSSA hybrid algorithm has been designed and used in solving the problem.

3 | Problem Definition

In this section, the definition of the problem and the design of a FB network under uncertainty have been discussed. The FB network according to *Fig. 1* includes a set of food donors, financial donors, FBs and charities. Food donors can provide hot and cold food. In this network, there are important decision variables such as allocation the donors to FBs, the optimal amount of cold food stock in the FB, and

JARIE

Ghahremani-Nahr et al.| J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540

the optimal vehicle routing for distribution the food basket to charities. According to *Fig. 1*, charities present their demand of different food baskets (a collection of hot and cold food items) to FBs. FBs also provide food needed by charities from donors. Therefore, part of the food is provided through food donors and in case of shortage, other food is provided through financial donors. The supplied food is divided into two categories: cold food (high shelf-life) and hot food (low shelf-life). An important issue in distributing food baskets to charities is the freshness of the food. In this model, the freshness of the food basket has an inverse relationship with the time of the food basket distribution. According to *Fig. 2*, as the time of food basket distribution to charities increases, the freshness of the food basket decreases exponentially. Therefore, in the mathematical model, in addition to cost management under the objective function of minimizing the total costs, maximization of the minimum freshness of the food basket has also been considered.

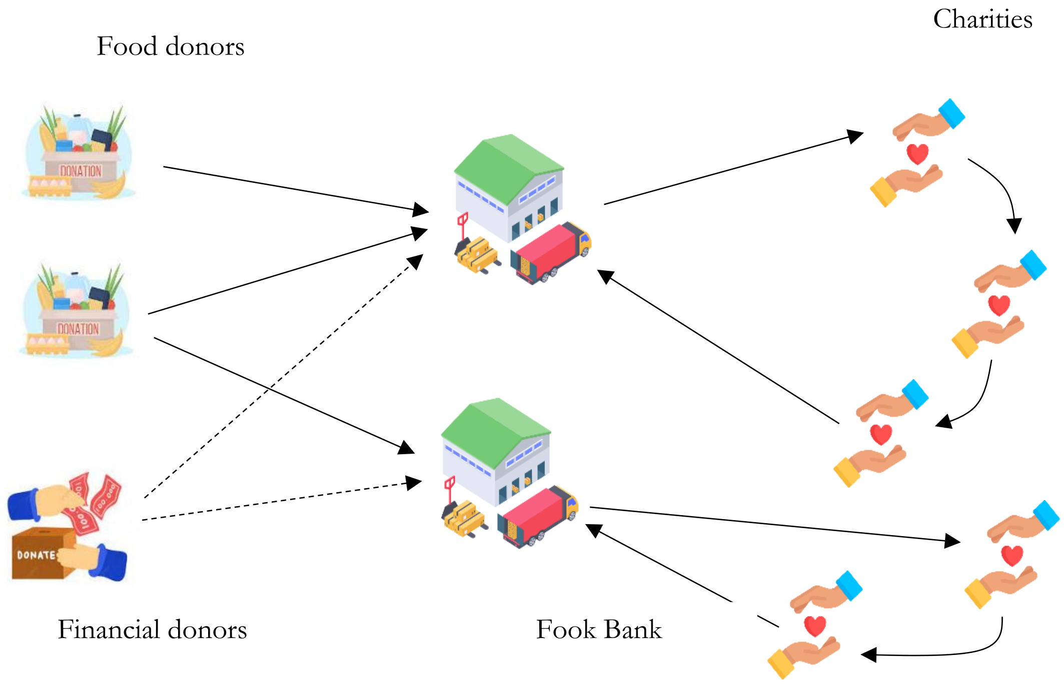

Fig. 1. The proposed model of the FB network.

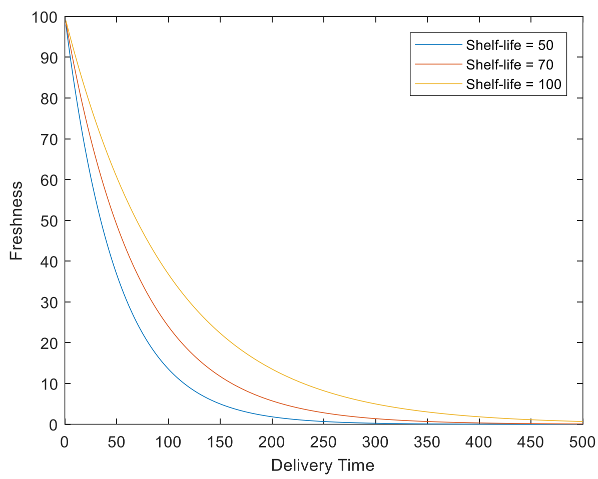

Fig. 2. Food freshness at the moment of delivery of the food basket to charities.

According to *Fig. 2*, it can be seen that the higher the food shelf-life, the higher its freshness also over time. In order to optimize the mentioned objective functions and achieve the decision variables, the following assumptions are presented for modeling:

I. The model is multi-echelon, multi-product and multi-period.
II. Food is considered in two types (cold and hot).
III. The total demand of charities must be met.
IV. There is a spending limit in buying food in each period.
V. Vehicles are heterogeneous and have different capacities.
VI. Time to collect food from donors is considered insignificant.

According to the above assumptions, parameters and decision variables for modeling the FB network problem have been introduced in the following:

Sets

I'	Set of food donors ($i = 1,2, \dots, I'$).
I''	Set of financial donors ($i = I' + 1, \dots, I''$).
I	Set of total donors ($i \in I' \cup I''$).
L	Set of FBs ($l, l' = 1,2, \dots, L$).
C	Set of charities ($c = 1,2, \dots, C$).
N	Set of total FBs and charities ($n, n' \in L \cup C$).
V	Set of vehicles ($v = 1,2, \dots, V$).
T	Set of periods ($t = 1,2, \dots, T$).
P	Set of food baskets ($p = 1,2, \dots, P$).
P'	Set of cold donated food (high shelf-life) ($e = 1,2, \dots, P'$).
P''	Set of high donated food (low shelf-life) ($e = P' + 1, \dots, P''$).

Parameters

g_v	The cost of using vehicle $v \in V$.
$o_{l,p}$	The operational cost of packing and distributing food basket $p \in P$ in FB $l \in L$.
$\tilde{\xi}_{n,n'}$	The transportation cost from node $n \in N$ to $n' \in N$.
$\tilde{\xi}'_{i,l}$	The transportation cost from donor $i \in I$ to FB $l \in L$.
$h_{e,t}$	The storage cost of cold food $e \in P'$ in period $t \in T$.
$\tilde{d}_{c,p,t}$	Demand of charity $c \in C$ of food basket $p \in P$ in period $t \in T$.
$\psi_{l,p}$	Maximum capacity of FB $l \in L$ from food basket $p \in P$.
$\tilde{\omega}_{i,e,t}$	Maximum food $e \in P' \cup P''$ donated from food donor $i \in I'$ in period $t \in T$.
γ_v	Maximum capacity of vehicle $v \in V$.
$k_{n,n'}$	The transportation time from node $n \in N$ to $n' \in N$.
φ_c	The service time at charity $c \in C$.
$\delta_{e,p}$	The number of foods $e \in P' \cup P''$ placed in food basket $p \in P$.
$\Omega_{i,e,t}$	The purchase cost of food $e \in P' \cup P''$ by financial donor $i \in I''$ in period $t \in T$.
s_{it}	The amount spent by financial donor $i \in I''$ to buy food in period $t \in T$.
u_p	The shelf-life of food basket $p \in P$.

Decision variables

$W_{l,p,v,t}$	The number of food basket $p \in P$ distributed from FB $l \in L$ by vehicle $v \in V$ in period $t \in T$.
$D_{c,v,t}$	The arrival time of vehicle $v \in V$ to charity $c \in C$ in period $t \in T$.
$F_{c,v,p,t}$	The freshness of food basket $p \in P$ distributed by vehicle $v \in V$ at the moment of arrival to charity $c \in C$ in period $t \in T$.
$Y_{i,l,e,v,t}$	The number of foods $e \in P' \cup P''$ collected from food donor $i \in I' \cup I''$ and shipped to FB $l \in L$ by vehicle $v \in V$ in period $t \in T$.
$Q_{l,e,t}$	Inventory of cold food $e \in P'$ at FB $e \in P'$ in period $t \in T$.
$U_{c,v,t}$	Auxiliary variable for subtours elimination.

Ghahremani-Nahr et al. | J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540

$X_{n,n',v,t}$	Equals is 1, if vehicle $v \in V$ passes from node $n \in N$ to node $n' \in N$ in period $t \in T$; otherwise is 0.
$R_{l,c,v,t}$	Equals is 1, if vehicle $v \in V$ used to dispatch food from FB $l \in L$ to charity $c \in C$ in period $t \in T$; otherwise is 0.
$A_{v,t}$	Equals is 1, if vehicle $v \in V$ used to collection the food from donors; otherwise is 0.
$B_{v,t}$	Equals is 1, if vehicle $v \in V$ used to distribution the food basket to charities; otherwise is 0.

According to the defined symbols, the non-linear integer mathematical programming model in the FB network design is as follows:

$$\begin{aligned} \text{Min OBF}_1 = & \sum_{v\in V}\sum_{t\in T} g_v.\left(A_{v,t}+B_{v,t}\right) + \sum_{l\in L}\sum_{p\in P}\sum_{v\in V}\sum_{t\in T} o_{l,p}.W_{l,p,v,t} \\ & + \sum_{n\in N}\sum_{n'\in N}\sum_{v\in V}\sum_{t\in T} \tilde{\xi}_{n,n'}.X_{n,n',v,t} \\ & + \sum_{i\in I}\sum_{l\in L}\sum_{e\in P'\cup P''}\sum_{v\in V}\sum_{t\in T} \tilde{\xi}'_{i,l}.Y_{i,l,e,v,t} + \sum_{l\in L}\sum_{e\in P'}\sum_{t\in T} h_{e,t}.Q_{l,e,t}, \end{aligned} \quad (1)$$

$$\text{Max OBF}_2 = \min_{c,p,v,t} Fr_{c,v,p,t}, \quad (2)$$

s. t.

$$\sum_{v\in V}\sum_{n\in N} X_{n,c,v,t} = 1, \quad \text{for all } c \in C, t \in T, \quad (3)$$

$$\sum_{n'\in N} X_{n',n,v,t} = \sum_{n'\in N} X_{n,n',v,t}, \quad \text{for all } v \in V, n \in N, t \in T, \quad (4)$$

$$\sum_{l\in L}\sum_{c\in C} X_{l,c,v,t} \le 1, \quad \text{for all } v \in V, t \in T, \quad (5)$$

$$\sum_{v\in V} R_{l,c,v,t} \le 1, \quad \text{for all } l \in L, c \in C, t \in T, \quad (6)$$

$$-R_{l,c,v,t} + \sum_{n\in N}\left(X_{l,n,v,t} + X_{n,c,v,t}\right) \le 1, \quad \text{for all } l \in L, c \in C, v \in V, t \in T, \quad (7)$$

$$U_{c,v,t} - U_{c',v,t} + |C|X_{c,c',v,t} \le |C| - 1, \quad \text{for all } c, c' \in C, v \in V, t \in T, \quad (8)$$

$$W_{l,p,v,t} \ge \sum_{c\in C} \tilde{d}_{c,p,t}.R_{l,c,v,t}, \quad \text{for all } l \in L, p \in P, v \in V, t \in T, \quad (9)$$

$$\sum_{c\in C}\sum_{n\in N}\sum_{p\in P} \tilde{d}_{c,p,t}.X_{n,c,v,t} \le \gamma_v.B_{v,t}, \quad \text{for all } v \in V, t \in T, \quad (10)$$

$$\sum_{v\in V} W_{l,p,v,t} \le \psi_{l,p}, \quad \text{for all } l \in L, p \in P, t \in T, \quad (11)$$

$$D_{c,v,t} \ge k_{l,c} - \text{BigM}.\left(1 - X_{l,c,v,t}\right), \quad \text{for all } l \in L, c \in C, v \in V, t \in T, \quad (12)$$

$$D_{c',v,t} \ge D_{c,v,t} + k_{c,c'} + \varphi_{c'} - \text{BigM}.\left(2 - X_{c,c',v,t} - R_{l,c,v,t}\right), \quad \text{for all } l \in L, c, c' \in C, v \in V, t \in T, \quad (13)$$

$$F_{c,v,p,t} \ge 100e^{-\frac{D_{c,v,t}}{u_p}} - \text{BigM}.\left(1 - R_{l,c,v,t}\right), \quad \text{for all } l \in L, c \in C, p \in P, v \in V, t \in T, \quad (14)$$

$$F_{c,v,p,t} \le 100e^{-\frac{D_{c,v,t}}{u_p}}, \quad \text{for all } c \in C, p \in P, v \in V, t \in T, \quad (15)$$

$$F_{c,v,p,t} \le \text{BigM}.R_{l,c,v,t}, \quad \text{for all } l \in L, c \in C, p \in P, v \in V, t \in T, \quad (16)$$

$$\sum_{i\in I}\sum_{v\in V} Y_{i,l,e,v,t} = \sum_{p\in P}\sum_{v\in V} \delta_{e,p}.W_{l,p,v,t}, \quad \text{for all } l\in L, e\in P'', t\in T, \tag{17}$$

$$Q_{l,e,t} = Q_{l,e,t-1} + \sum_{i\in I}\sum_{v=V} Y_{i,l,e,v,t} - \sum_{p\in P}\sum_{v\in V} \delta_{e,p}.W_{l,p,v,t}, \quad \text{for all } l\in L, e\in P', t \in T, \tag{18}$$

$$\sum_{l\in L}\sum_{v\in V} Y_{i,l,e,v,t} \le \widetilde{\omega}_{i,e,t}, \quad \text{for all } i\in I', e\in P'\cup P'', t\in T, \tag{19}$$

$$\sum_{i\in I}\sum_{e\in P'\cup P''}\sum_{l\in L} Y_{i,l,e,v,t} \le \gamma_v . A_{v,t}, \quad \text{for all } v\in V, t\in T, \tag{20}$$

$$\sum_{l\in L}\sum_{v\in V}\sum_{e\in P'\cup P''} \Omega_{i,e,t}.Y_{i,l,e,v,t} \le s_{i,t} + \sum_{t'\le t-1}\left(s_{i,t'} - \sum_{l\in L}\sum_{v\in V}\sum_{e\in P'\cup P''} \Omega_{i,e,t'}.Y_{i,l,e,v,t'}\right) \quad \text{for all } i\in I'', t \in T, \tag{21}$$

$$D_{c,v,t} \le M.R_{l,c,v,t}, \quad \text{for all } l\in L, c\in C, v\in V, t\in T, \tag{22}$$

$$X_{l,l',v,t} \le 0, \quad \text{for all } l,l'\in L, v\in V, t\in T, \tag{23}$$

$$D_{c,v,t}, F_{c,v,p,t}, Q_{l,e,t}, U_{c,v,t} \ge 0, \tag{24}$$

$$R_{l,c,v,t}, X_{n,n',v,t}, A_{v,t}, B_{v,t} \in \{0,1\}, \tag{25}$$

$$W_{l,p,v,t}, Y_{i,l,e,v,t} \ge 0 \text{ and integer.} \tag{26}$$

Eq. (1) shows the first objective function of the problem and includes the total costs of the FB network design. These costs, respectively, include the costs of using vehicles, transportation costs, and the inventory costs. *Eq. (2)* shows the second objective function of the problem and includes the maximization of the minimum freshness of food packages distributed to charities. *Eq. (3)* guarantees that in each period, one of the total vehicles is allowed to dispatch food baskets to each charity. *Eq. (4)* shows that every vehicle must leave that node after distributing food packages to a charity. *Eqs. (5)* and *(6)* guarantees that at most one vehicle can visit a set of charities in each time period. *Eq. (7)* shows that the starting point and end point of visits to charities by any vehicle is the FB. *Eq. (8)* is the equation related to the subtours elimination. *Eq. (9)* calculates the amount of food baskets distributed by each FB according to uncertain demand. *Eq. (10)* also shows the limitation of vehicle capacity in distributing food baskets to charities. *Eq. (11)* guarantees that the amount of food baskets distributed by each FB is less than the maximum capacity. *Eqs. (12)* and *(13)* calculate the arrival time for the vehicle to the charities for the distribution of food baskets. *Eqs. (14)* to *(16)* calculate the freshness of food baskets at the moment of their distribution to charities. *Eq. (17)* shows the number of hot foods (low shelf-life) needed to supply food baskets. *Eq. (18)* shows the number of cold foods (high shelf-life) in each of the FBs. *Eq. (19)* shows the maximum donated of hot and cold food by donors. *Eq. (20)* shows the number of vehicles used to collect hot and cold food from donors. *Eq. (21)* shows the amount of funds available for buying hot and cold food from other donors in each period. *Eqs. (22)* and *(23)* show logical relationships between decision variables. *Eqs. (24)* to *(26)* show the type of decision variables.

In this paper, in order to deal with the uncertainties in the parameters of the model, which includes parameters of supply, demand and transportation costs, Jimenez's fuzzy method is used due to its high efficiency. In addition to maintaining the linearity of the problem, this method does not increase the number of objective functions and inequality constraints. Jimenez et al. [57] fuzzy method is programmed based on the expected value and the expected interval. Due to the computational efficiency and simplicity, the triangular fuzzy distribution method has been used to deal with the inaccurate parameters of the model. Suppose $\tilde{C}$ is a triangular fuzzy number, the membership function of this fuzzy number $\mu\tilde{C}(x)$ is defined as *Relation (27)*:

$$\mu\widetilde{C}(x) = \begin{cases} f_c(x) = \dfrac{x - c_p}{c_m - c_p}, & \text{if } c_p \leq x \leq c_m, \\ 1, & \text{if } x = c_m, \\ g_c(x) = \dfrac{c_o - x}{c_o - c_m}, & \text{if } c_m \leq x \leq c_o, \\ 0, & \text{if } x < c_p \text{ or } x > c_o. \end{cases} \tag{27}$$

The expected distance EI and the mathematical expectation EV of the triangular fuzzy number are calculated from the following relations:

$$EI(\widetilde{C}) = [E_1^c, E_2^c] = \left[\int_0^1 f_c^{-1}(x)dx, \int_0^1 g_c^{-1}(x)dx\right] = \left[\frac{1}{2}(c_m + c_p), \frac{1}{2}(c_o + c_m)\right]. \tag{28}$$

$$EV(\widetilde{C}) = \frac{E_1^c + E_2^c}{2} = \frac{c_p + 2c_m + c_o}{4}. \tag{29}$$

For the pair of fuzzy numbers $\tilde{a}$ and $\tilde{b}$, the degree of $\tilde{a}$ being greater than $\tilde{b}$ is defined by the following relation:

$$\mu_M(\tilde{a}, \tilde{b}) = \begin{cases} 1, & \text{if } E_1^a > E_2^b, \\ \dfrac{E_2^a - E_1^b}{E_2^a - E_1^b - (E_1^a - E_2^b)}, & \text{if} 0 \epsilon [E_1^a - E_2^b, E_2^a - E_1^b], \\ 0, & \text{if } E_2^a < E_1^b. \end{cases} \tag{30}$$

$\mu_M(\tilde{a}, \tilde{b}) \geq \alpha$ mean that at least in degree α, $\tilde{a}$ greater than $\tilde{b}$ is equal and defined as $\tilde{a} \geq_\alpha \tilde{b}$. In addition, for the pair of fuzzy numbers $\tilde{a}$ and $\tilde{b}$ where $\tilde{a}$ is equal to $\tilde{b}$, we have $\tilde{a} \geq_{\frac{\alpha}{2}} \tilde{b}, \tilde{a} \leq_{\frac{\alpha}{2}} \tilde{b}$. Now consider the following fuzzy programming model in which all non-deterministic parameters are considered as fuzzy:

$$\begin{aligned} &\text{Min } Z = \tilde{c}^t x, \\ &\tilde{a}_i x \geq \tilde{b}_i \quad \text{for all } i = 1,2, \dots, l, \\ &\tilde{a}_i x = \tilde{b}_i \quad \text{for all } i = l+1, \dots, m, \\ &x \geq 0. \end{aligned} \tag{31}$$

According to the Jimenez method, for the case where $\tilde{a}$ is greater than $\tilde{b}$ we have:

$$\frac{E_2^{a_i x} - E_1^{b_i}}{E_2^{a_i x} + E_1^{b_i} - E_1^{a_i x} - E_2^{b_i}} \geq \alpha \quad \text{for all } i = 1, \dots, l. \tag{32}$$

For the case where $\tilde{a}$ is equal to $\tilde{b}$ we have:

$$\frac{\alpha}{2} \leq \frac{E_2^{a_i x} - E_1^{b_i}}{E_2^{a_i x} + E_1^{b_i} - E_1^{a_i x} - E_2^{b_i}} \leq 1 - \frac{\alpha}{2} \quad \text{for all } i = l+1, \dots, m. \tag{33}$$

According to the above relations, we have:

$$\begin{aligned} &[(1-\alpha)E_2^{a_i x} + \alpha E_1^{a_i x}]x \geq (1-\alpha)E_1^{b_i} + \alpha E_2^{b_i} \quad \text{for all } i = 1, \dots, l, \\ &\left[\left(1 - \frac{\alpha}{2}\right)E_2^{a_i x} + \frac{\alpha}{2}E_1^{a_i x}\right]x \geq \left(1 - \frac{\alpha}{2}\right)E_1^{b_i} + \frac{\alpha}{2}E_2^{b_i} \quad \text{for all } i = l+1, \dots, m, \\ &\left[\left(1 - \frac{\alpha}{2}\right)E_1^{a_i x} + \frac{\alpha}{2}E_2^{a_i x}\right]x \leq \left(1 - \frac{\alpha}{2}\right)E_2^{b_i} + \frac{\alpha}{2}E_1^{b_i} \quad \text{for all } i = l+1, \dots, m. \end{aligned} \tag{34}$$

According to the stated relationships, the final controlled model of the FB Network is as follows:

$$\text{Min OBF}_1 = \sum_{v\in V}\sum_{t\in T} g_v.\left(A_{v,t} + B_{v,t}\right) + \sum_{l\in L}\sum_{p\in P}\sum_{v\in V}\sum_{t\in T} o_{l,p}.W_{l,p,v,t} +$$

$$\sum_{n\in N}\sum_{n'\in N}\sum_{v\in V}\sum_{t\in T}\left(\frac{\xi^{(o)}_{n,n'} + 2.\,\xi^{(m)}_{n,n'} + \xi^{(p)}_{n,n'}}{4}\right).X_{n,n',v,t} + \quad (35)$$

$$\sum_{i\in I}\sum_{l\in L}\sum_{e\in P'\cup P''}\sum_{v\in V}\sum_{t\in T}\left(\frac{\xi'^{(o)}_{i,l} + 2.\,\xi'^{(m)}_{i,l} + \xi'^{(p)}_{i,l}}{4}\right).Y_{i,l,e,v,t} + \sum_{l\in L}\sum_{e\in P'}\sum_{t\in T} h_{e,t}.Q_{l,e,t},$$

$$\text{Max OBF}_2 = \min_{c,p,v,t} Fr_{c,v,p,t}, \quad (36)$$

s. t.

$$W_{l,p,v,t} \geq \sum_{c\in C}\left(\alpha.\frac{d^{(m)}_{c,p,t} + d^{(p)}_{c,p,t}}{2} + (1-\alpha).\frac{d^{(o)}_{c,p,t} + d^{(m)}_{c,p,t}}{2}\right).R_{l,c,v,t}, \quad \text{for all } l \in L, p \in P, v \in V, t \in T, \quad (37)$$

$$\sum_{c\in C}\sum_{n\in N}\sum_{p\in P}\left(\alpha.\frac{d^{(m)}_{c,p,t} + d^{(p)}_{c,p,t}}{2} + (1-\alpha).\frac{d^{(o)}_{c,p,t} + d^{(m)}_{c,p,t}}{2}\right).X_{n,c,v,t} \leq \gamma_v.B_{v,t}, \quad \text{for all } v \in V, t \in T, \quad (38)$$

$$\sum_{l\in L}\sum_{v\in V} Y_{i,l,e,v,t} \leq \left(\alpha.\frac{\omega^{(o)}_{i,e,t} + \omega^{(m)}_{i,e,t}}{2} + (1-\alpha).\frac{\omega^{(m)}_{i,e,t} + \omega^{(p)}_{i,e,t}}{2}\right), \quad \text{for all } i \in I', e \in P' \cup P'', t \in T, \quad (39)$$

$$\text{Eqs}(3-8), (11-18), (20-26). \quad (40)$$

4 | Solution Method

The FB network model designed in this paper includes a routing-inventory-allocation problem. It has been proven in the subject literature that routing-allocation problems are among NP-hard problems and to solve these problems, heuristic or meta-heuristic methods should be used. Therefore, the degree of difficulty of the proposed model is at least equal to the degree of difficulty of the routing-allocation problems and hence it is considered as one of the NP-hard problems. Also, due to the dual purpose of the mathematical model, multi-objective meta-heuristic algorithms should be used. In this section, after designing the initial solution, the HGSSA has been described.

4.1 | Initial Solution Design

The most important part in using the algorithm is designing the initial solution and decoding it in a way that can solve the problem under investigation. The FB network problem consists of various decision strategies. According to *Fig. 3*, in the first part, decisions are related to the amount of food basket supply (demand fulfillment), in the second part, decisions are related to vehicle routing, and in the third part, they are related to the optimal allocation of food/finance donors to the FBs. *Fig. 3* shows how the initial solution is displayed for five charities, three FBs and four food/financial donors, three vehicle types and for only one period and one product type.

Ghahremani-Nahr et al.| J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540

Node	|I| + |J|							|C|				
	i_1	i_2	i_3	i_4	j_1	j_2	j_3	c_1	c_2	c_3	c_4	c_5
Rand()	6	1	3	4	2	5	7	1	3	5	2	4
Vehicle	3	2	1	3	-	-	-	1	2	1	2	1

Fig. 3. Initial solution of FB.

Fig. 3 shows the initial solution in a $2 * (|I| + |J| + |C|)$ matrix. To decode, we will follow the steps below in each section:

Step 1. Decoding the vehicle routing section.

In this part, based on the solution presented in the first section, the sequence of visiting charities by each vehicle and the amount of demand supplied from each FB is determined. According to *Fig. 3*, it can be seen that vehicle number 1 will visit charities number 1, 5 and 3 respectively. Also, vehicle number 2 will meet the demand of charities 4 and 2, respectively. If the amount of food transported by each vehicle is more than the capacity of the allocated vehicle, the demand of high-priority charities will be met with another vehicle.

Step 2. Decoding the selection of FBs.

To determine the FBs for the distribution of food baskets, first the highest priority among the FBs is selected. If this center alone cannot meet the total demand of charities, FBs with the next higher priority will be selected. According to *Fig. 4*, two FBs number 2 and 3 are selected to meet the demand of charities; therefore, there is no need to use FB number 1. In this case, the priority of FB number 1 will be reduced to 0.

Step 3. Decoding the flow allocation between donors and FBs.

In this part, based on the amount of food distribution by FBs and the donation capacity of charities, the optimal flow allocation is done based on the modified chromosome in the previous section (*Fig. 4*).

Node	|I| + |J|						
	i_1	i_2	i_3	i_4	j_1	j_2	j_3
Rand()	6	1	3	4	0	5	7
Vehicle	3	2	1	3	-	-	-

Fig. 4. Modified solution of optimal flow allocation segment.

For optimal flow allocation, the following steps are performed:

I. The highest priority among the modified solution is selected as the starting part of the allocation.
II. The donor/FB is selected based on the lowest transportation cost with the FB/donor obtained from *Step 1*.
III. The vehicle needed to transport food between two echelons is selected.
IV. The optimal flow allocation between the selected echelons is obtained based on the minimum amount (donor supply, FB demand and vehicle capacity).
V. Donor supply and FB demand are updated.
VI. If the donor supply or the FB demand becomes zero, the priority associated with that echelon will be reduced to 0.
VII. *Steps 1* to *6* continue until the total donor priority is reduced to 0.
VIII. If all the priorities of the FB are not 0, financial donors will be used to supply the food to meet the remaining FBs demand.

According to the three sections presented in this section, the search space of the FB network problem can be investigated and the optimal values of the objective functions can be achieved.

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4.2 | HGSSA Algorithm

The main inspiration for the Salp Swarm Algorithm (SSA) is the social behavior of a marine organism called Salps. Salps are barrel-shaped and free-floating animals from the Salpidae family [58]. SSA is a population-based algorithm and starts by adopting a random initialization of organisms. Each of these entities is a candidate solution to the objective function problem. There are two types of organisms in a swarm of salps: leaders and followers. The leader is the first chain that guides the followers in their movement. A swarm X of salps is formed that can be represented by a two-dimensional matrix (*Eq. (41)*). The purpose of this swarm is to search for a food source in a search space called F [59], [60].

$$X_i = \begin{bmatrix} X_1^1 & \cdots & X_d^1 \\ \vdots & \ddots & \vdots \\ X_1^n & \cdots & X_d^n \end{bmatrix}. \tag{41}$$

The position of the leader is updated using *Eq. (42)*:

$$X_1^1 = \begin{cases} F_j + c_1\left(\left(ub_j - lb_j\right)c_2\right) + lb_j, c_3 \geq 0.5, \\ F_j - c_1\left(\left(ub_j - lb_j\right)c_2\right) + lb_j, c_3 < 0.5, \end{cases} \tag{42}$$

where F_j and X_1^1 are the leader's position and food source in dimension j, respectively. c_1 is a variable that gradually decreases during the round and is calculated based on *Eq. (43)*. In this relationship, l and L are the current and the maximum iterations, respectively.

$$c_1 = 2e^{-\left(\frac{4l}{L}\right)^2}. \tag{43}$$

Parameters c_2 and c_3 are also two random numbers in the [0,1] interval. Also, ub_j and lb_j are the upper and lower bounds of each variable in the initial solution, which are equal to 0.2 and 0 in this paper. The position of salps is also updated using *Eq. (44)*:

$$X_j^i = \frac{1}{2}\left(X_j^i - X_j^{i-1}\right), \tag{44}$$

where X_j^i represents the i[th] position of the follower salp in dimension j. On the other hand, after determining the position of the salps, in this method, two crossover and mutation operators of the Genetic Algorithm (GA) have been used to improve the candidate solutions. Therefore, after determining the position of follower, according to the crossover rate (pc) and mutation rate (pm), new solutions are created as described in *Figs. 5* and *6*. *Fig. 5* shows how to perform the crossover operator on follower salp. In this form, both salps are introduced as parents, and after performing the two-point crossover operator, the following salps are created as children. In this operator, proportional to the crossover rate, two random points are created in salp genes and moved with each other.

Salp 1 (Parent 1)	0.10	0.15	0.16	0.05	0.18	0.07	0.14	0.19
Salp 2 (Parent 2)	0.13	0.16	0.15	0.07	0.01	0.02	0.14	0.13
Sapl 1 (Child 1)	0.10	0.15	0.16	0.07	0.01	0.02	0.14	0.19
Salp 2 (Child 2)	0.13	0.16	0.15	0.05	0.18	0.07	0.14	0.13

Fig. 5. The two-point crossover operator.

Also, one of the most important operators of the GA is the mutation operator, in which a gene from the leader salp takes on a new value randomly. Therefore, in *Fig. 6* it is shown how to perform the single-point mutation operator.

Ghahremani-Nahr et al. | J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540

Salp 2 (Parent 2)	0.10	0.15	0.16	0.07	0.18	0.02	0.14	0.19
Sapl 1 (Child 1)	0.10	0.15	0.16	0.07	0.01	0.02	0.14	0.19

Fig. 6. The single point mutation operator.

Algorithm 1 also presents the pseudo code of the HGSSA.

Algorithm 1. HGSSA pseudo code.

Input: *n*: *Number of Salp in the pack*
  L: *Number of Max iteration*
  pm : *Mutation rate*
  pc: *Crossover rate*
Output: *F Optimal Salp position* (*Best position*)
  $f(F)$ *fitness values*
1. *Initialize a population of n Salp positions at random* $\in [0, 0.2]$
2. *Calculate the fitness of each search agent* (*Salp positions*)
3. ***While*** *Stopping criteria not met do*
  Update c_1 *using Eq.* (43)
  for each *Salp* ***do***
   if $(i == 1)$
    Update the ***leading*** *Salp positions by the Eq* (42)
   else
    Update the ***follower*** *Salp positions by the Eq.* (44)
   end
   do Crossover operator for 2 *candidate Sapls based on Fig.* (5)
   do Mutation operator for any candidate Salp based on Fig. (6)
  end
  Update F
end While
4. *Return F.*

5 | Analysis of Sample Problems

After presenting the mathematical model of the FB and also designing the appropriate solution method, in this section, various sample problems are presented to check the outputs of the model. *Table 2* shows different sample problems in different scales. Also, *Table 3* shows the parameters of the mathematical model in two sections, deterministic and uncertainty parameters.

Table 2. Sample problems designed for the FB.

Sample Problem	Scale	$(I' \times I'' \times L \times C \times V \times T \times P \times P' \times P'')$
1		$(3 \times 2 \times 3 \times 6 \times 10 \times 3 \times 2 \times 2 \times 2)$
2		$(3 \times 2 \times 3 \times 8 \times 10 \times 3 \times 2 \times 2 \times 2)$
3	Small	$(4 \times 2 \times 4 \times 10 \times 10 \times 4 \times 3 \times 3 \times 3)$
4		$(4 \times 3 \times 4 \times 12 \times 12 \times 4 \times 3 \times 3 \times 3)$
5		$(5 \times 3 \times 5 \times 15 \times 12 \times 6 \times 4 \times 4 \times 3)$
6		$(5 \times 3 \times 5 \times 18 \times 12 \times 6 \times 4 \times 4 \times 3)$
7		$(7 \times 4 \times 5 \times 21 \times 15 \times 8 \times 5 \times 4 \times 3)$
8	Medium	$(7 \times 4 \times 6 \times 25 \times 15 \times 8 \times 5 \times 4 \times 4)$
9		$(10 \times 5 \times 6 \times 28 \times 15 \times 10 \times 5 \times 5 \times 4)$
10		$(10 \times 6 \times 8 \times 30 \times 18 \times 10 \times 6 \times 5 \times 4)$
11		$(12 \times 8 \times 8 \times 35 \times 18 \times 12 \times 6 \times 5 \times 4)$
12		$(12 \times 8 \times 10 \times 40 \times 18 \times 12 \times 6 \times 6 \times 4)$
13	Large	$(15 \times 10 \times 12 \times 45 \times 21 \times 12 \times 8 \times 6 \times 4)$
14		$(18 \times 12 \times 15 \times 50 \times 25 \times 15 \times 8 \times 6 \times 5)$
15		$(20 \times 15 \times 18 \times 60 \times 30 \times 15 \times 10 \times 6 \times 5)$

Table 3. Value of deterministic and uncertainty parameters of FB.

Deterministic Parameter	Value	Deterministic Parameter	Value
g_v	~U(300,400)	φ_c	~U(5,8)
$o_{l,p}; h_{e,t}$	~U(2,3)	$\delta_{e,p}$	~U(1,3)
$\psi_{l,p}$	~U(200,220)	$\Omega_{i,e,t}$	~U(1,5)
γ_v	~U(60,80)	s_{it}	5000
$k_{n,n'}$	~U(15,20)	u_p	~U(60,900)
Uncertainty Parameter	**Optimistic**	**More Likely**	**Pessimistic**
$\tilde{\xi}_{n,n'}$	~U(20,25)	~U(25,30)	~U(30,40)
$\tilde{\xi}'_{i,l}$	~U(5,10)	~U(10,15)	~U(15,20)
$\tilde{d}_{c,p,t}$	~U(20,30)	~U(30,40)	~U(40,50)
$\tilde{\varpi}_{i,e,t}$	~U(100,120)	~U(120,150)	~U(150,180)

In this paper, the values of the model parameters are considered randomly and according to the uniform distribution function. Also, the value of uncertainty rate in solving sample problems is assumed equal to 0.5. Before analyzing sample problems in different scales, the parameters of the GA, SSA and HGSSA are tuning. This is to increase the efficiency of algorithms in solving sample problems. The method used to tune the parameters is the Taguchi method. In this method, various tests are performed according to the defined levels and after normalizing the results and using the NPF, MSI, SM, MID and CPU-Time indicators, the best levels of the parameters are shown to increase the efficiency of the algorithms (GA, SSA, HGSSA). *Table 4* shows the suggested levels of parameters, the best selected levels and the value of each factor in the proposed algorithms.

Table 4. The results of parameter tuning with Taguchi method.

Algorithm	Parameter	Suggested Level L1	L2	L3	Best Level	Best Value
GA	Npop	100	150	200	L3	200
	Max it	100	200	400	L3	400
	Pc	0.7	0.8	0.9	L2	0.8
	Pm	0.05	0.07	0.09	L1	0.05
SSA	N Salp	100	150	200	L3	200
	L	100	200	400	L3	400
	c_1	0.2	0.1	0.01	L2	0.01
HGSAA	N Salp	100	150	200	L3	200
	L	100	200	400	L3	400
	c_1	0.2	0.1	0.01	L1	0.2
	Pc	0.7	0.8	0.9	L1	0.7
	Pm	0.05	0.07	0.09	L2	0.07

The optimal value of the parameters obtained from *Table 4* leads to an increase in the efficiency of the solution methods in solving sample problems. On the other hand, in order to ensure the obtained results, each sample problem has been executed 3 times by each algorithm. After solving the sample problems, *Table 5* shows the value of the indices obtained from solving each sample problem by each solution method.

The results of *Table 5* show that the CPU-time has increased exponentially by increasing the scale of the problem. This shows the Np-Hardness of FB. On the other hand, by examining other indicators, it was observed that GA has the lowest NPF and HGSSA the highest NPF value. In the study of the MSI index, GA has obtained the highest value. While SSA has obtained the lowest amount of SM and HGSSA has obtained the lowest amount of MID. These results show that the solution methods have been more efficient in solving the sample problems and the maximum time to solve the problem was only 712.11 seconds. *Fig. 8* shows the value of each index in different sample problems.

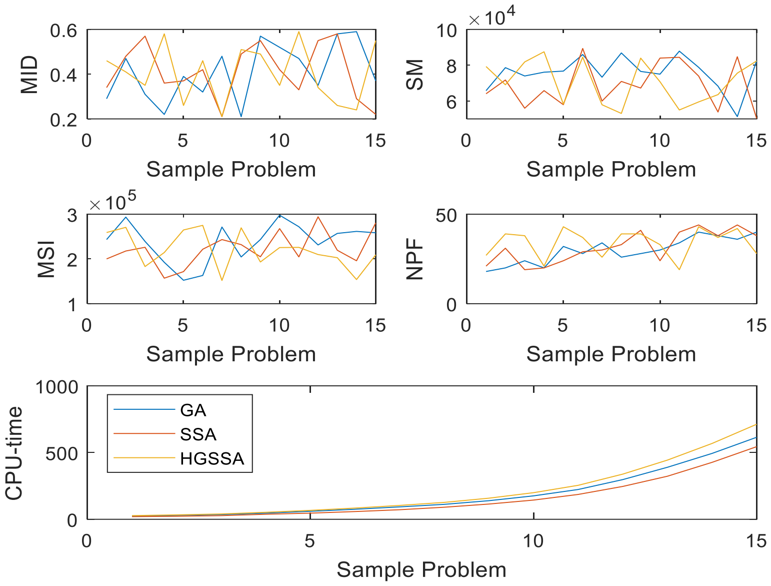

Fig. 8. The trend of computational indicators in different sample problems.

Table 5. The indicators obtained from solving sample problems.

Sample Problem	GA					SSA					HGSSA				
	NPF	MSI	SM	MID	CPU-Time	NPF	MSI	SM	MID	CPU-Time	NPF	MSI	SM	MID	CPU-Time
1	18	243393	65765.1	0.29	24.28	21	200089	64040.9	0.34	19.91	27	259114	79258.9	0.46	27.56
2	20	293576	78629.7	0.47	29.67	31	217777	71733.0	0.48	22.85	39	270671	69051.6	0.41	33.15
3	24	239220	73978.5	0.31	35.71	19	226075	55960.5	0.57	27.50	38	183039	81837.8	0.35	39.90
4	20	192471	76095.5	0.22	46.2	20	157031	65796.3	0.36	37.88	21	214360	87490.1	0.58	52.45
5	32	152345	76703.9	0.39	59.94	24	171678	57917.9	0.37	46.15	43	264771	58244.2	0.26	66.96
6	28	163076	85971.4	0.32	75.34	29	221685	89332.1	0.42	58.01	37	275108	84501.9	0.46	84.17
7	34	271377	73300.1	0.48	93.11	30	243279	59948.1	0.21	71.69	26	151940	57894.8	0.21	104.02
8	26	204452	86846.4	0.21	112.04	33	232037	70935.3	0.49	90.46	39	269499	53047.6	0.51	126.68
9	28	243374	76525.9	0.57	139.41	41	204853	67235.4	0.55	114.32	39	193229	83949.9	0.49	158.26
10	30	297866	74997.9	0.52	175.66	24	267828	83974.2	0.42	144.04	33	225448	70745.7	0.35	199.41

Table 5. Continued.

Sample Problem	GA					SSA					HGSSA				
	NPF	MSI	SM	MID	CPU-Time	NPF	MSI	SM	MID	CPU-Time	NPF	MSI	SM	MID	CPU-Time
11	34	272066	87857.0	0.47	223.34	40	204645	84409.6	0.33	186.24	19	225877	54981.9	0.59	254.65
12	40	231301	78799.4	0.35	297.48	44	294195	73924.9	0.55	246.27	43	209855	59482.6	0.34	338.54
13	38	257110	68300.6	0.58	389.71	38	219468	53841.2	0.58	322.68	37	202759	63561.0	0.26	443.52
14	36	261605	51291.4	0.59	493.52	44	195936	84705.3	0.29	426.59	42	153987	75565.6	0.24	568.13
15	40	258500	82462.5	0.37	614.53	38	280593	50224.1	0.22	544.18	28	209236	82374.1	0.55	712.11

Table 6 shows the total average of comparison indicators for large-scale sample problems. According to the results of *Fig. 8*, it can be seen that there is not much difference in the average calculation indices between the solution methods. For example, *Fig. 9* shows the Pareto front of sample problem 1 obtained from the methods of GA, SSA, and HGSSA. In this Pareto front, the GA has obtained 18 efficient solutions, the SSA has obtained 21 efficient solutions, and the HGSSA has obtained 27 efficient solutions. Therefore, it can be concluded that the performance of HGSSA is higher than the GA and SSA. This is due to the use of the combined operators of two other algorithms in the search of the feasibility space, which has led to the achievement of more efficient solutions.

Table 6. Average comparison indices in large-scale sample problems.

Algorithm	NPF	MSI	SM	MID	CPU-Time
GA	29.87	238782.71	75835.02	0.41	187.33
SSA	31.73	222478.44	68931.92	0.41	157.25
HGSSA	34.07	220593.31	70799.18	0.40	213.97
Best Performance	HGSSA	GA	SSA	HGSSA	SSA

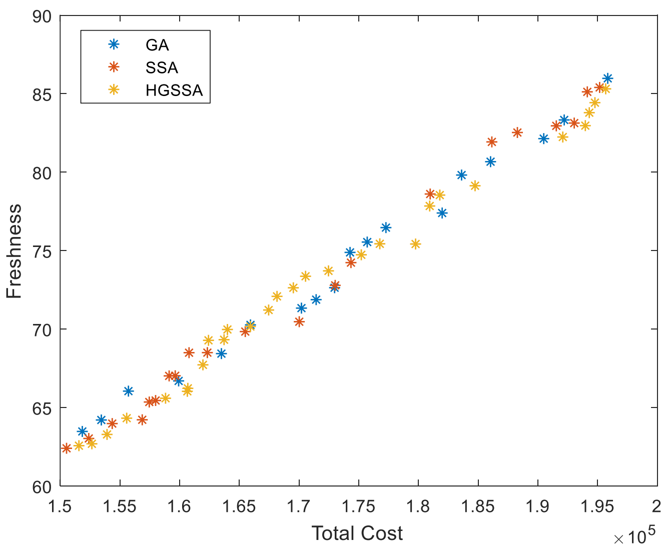

Fig. 9. Pareto front obtained from sample problem.

Increase in the total costs of the FB network, the minimum freshness of the food basket has also increased. This is due to the increase in transportation costs and the use of different vehicles in distributing food baskets to charities. Therefore, it can be concluded that by increasing the number of vehicles and changing the route of transportation of vehicles, at least the freshness of the food basket can be increased and higher quality food can be delivered to charities.

Fig. 10 also shows the amount of the main mathematical model variables using HGSSA. The results shown for the first efficient solution. The main variables of the problem include routing-inventory and optimal allocation for food basket 1 in period 1.

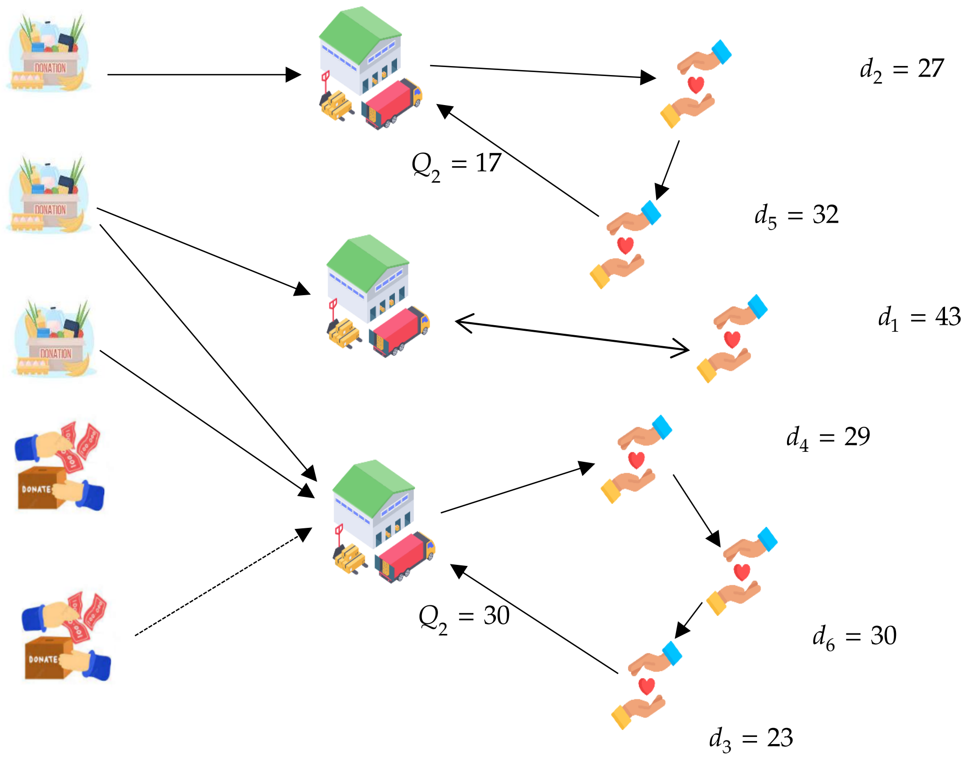

Fig. 10. The amount of the main variables of the FB problem.

In the analysis of *Fig. 10*, it can be stated that the freshness of food basket 1 is for charity No. 3 with a value of 62.2%. Also, FB No. 2 is solely responsible for transferring the food basket to Charity No. 1. On the other hand, it can be stated that the amount of cold food in FB No. 1 was equal to 17 and in FB No. 3 was equal to 30. In this example, FB No. 3 has also used financial donor No. 2 to estimate the demand of charities.

In the given example, the total cost of the FB was equal to 151570.34 units and the minimum freshness of the food basket was equal to 62.2. In order to investigate the influence of the uncertainty rate on the Objective Functions Values (OBFVs), a sensitivity analysis has been carried out. The uncertainty rate in this sensitivity analysis has changed from 0.1 to 0.9. *Table 7* shows the total cost of the FB and the minimum freshness of the food basket at different uncertainty rates.

Table 7 and the sensitivity analysis on the uncertainty rate show that with the increase of this parameter, due to the increase in the demand from charities and the increase in the number of vehicles, the total costs of the FB network have increased. On the other hand, due to the increase in the demand of charities and the reduction of food supply capacity, the distribution of food baskets has been delayed and this has led to a decrease in the freshness of the food basket.

Table 7. The OBFVs of the problem at different uncertainty rates.

Uncertainty Rate	Total Cost	Freshness
0.1	146352.75	73.14
0.2	148664.19	73.14
0.3	149325.91	70.67
0.4	150743.34	67.62
0.5	151570.34	62.25
0.6	152378.34	62.25
0.7	153687.64	62.25
0.8	154776.68	60.37
0.9	156742.63	60.37

On the other hand, due to the fact that the distributed food items have a shelf-life time, their influence on the freshness of the food baskets is greater. *Table 8* shows the sensitivity analysis on the shelf-life on the OBFVs of the problem.

Table 8. The OBFVs of the problem at different shelf-life.

Shelf-life Changes	Total Cost	Freshness
-20%	150345.27	75.33
-15%	150764.34	70.38
-10%	150934.25	66.81
-5%	151232.33	64.25
0	151570.34	62.25
+5%	151867.48	61.30
+10%	152348.67	60.25
+15%	152866.74	55.68
+20%	153178.67	54.36

By examining the changes in shelf-life on the values of the OBFVs according to *Table 8*, it can be seen that with the increase in shelf-life of food, the inventory cost and supplying food has decreased and has led to the reduction of total costs. Also, increasing the shelf-life of food has led to an increase in the minimum freshness of the food basket. *Fig. 11* also shows the changes of the OBFVs in the performed sensitivity analysis (uncertainty rate and shelf-life).

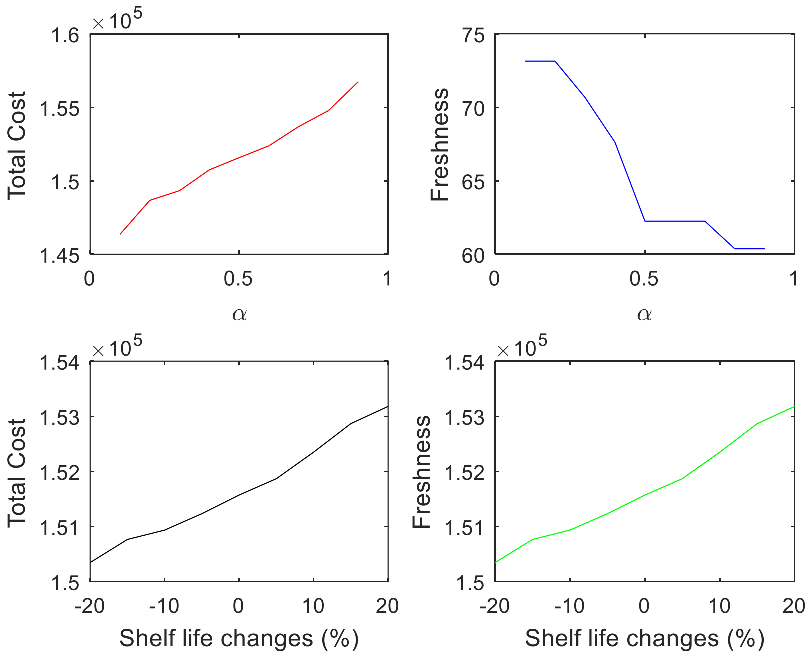

Fig. 11. Changes in the OBFVs in different analyses.

Ghahremani-Nahr et al. | J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540

6 | Conclusion and Future Study

Hunger knows no boundaries, and it's devastating impact is alarmingly similar to a poor community or a relatively wealthy region. Worldwide, 690 million people go to bed hungry, and about 14 million children under the age of five suffer from severe acute malnutrition, according to Action against Hunger. Poverty, climate change and political conflicts are all factors in this sad situation. FBs are one of the most efficient and cost-effective ways to ensure that hungrier people are fed. FBs collect and distribute safe, unsaleable food from anywhere in the supply chain—from farms to food manufacturers and retailers—that would otherwise go to waste. The importance of the above issue led to the creation of a FB network consisting of various decisions such as routing-inventory and allocation in order to meet the food needs of charities. The designed model simultaneously minimized the total costs of the FB network and maximized the minimum freshness of the food baskets. Today, only cost reduction is not important to meet people's needs, and providing healthy and high-quality food is important. Based on this and by using a new method of HGSSA and comparing it with GA and SSA, it was observed that in order to increase the freshness of food basket, more vehicles should be provided to the FB. This leads to an increase in the costs of the FB network. On the other hand, the greater the uncertainty in the FB network, the more the demand of charities and the less the capacity to donate food. The result of this is increasing the costs of the FB network and reducing the freshness of food basket. On the other hand, as the shelf-life of food and food baskets increases, the total costs of the FB network decrease and the freshness of food baskets increases.

These results help managers to be more careful in choosing vehicles to distribute food baskets and should use vehicles equipped with refrigerators. Also, due to the uncertainty in the environment, managers can estimate the total costs of the FB network and do not make the best decision regarding routing, inventory and allocation according to budgeting. Because this has a direct relationship with the amount of food stored in the FB. The limitations of this research are not considering the freshness of food at the moment of collecting it from donors. Therefore, it is necessary to consider this in future research.

In this paper, the efficiency of HGSSA was also investigated, and the results of solving problems with larger-scales sample problem showed that combining the operators of different algorithms leads to an increase in the search power of the algorithm. Therefore, in the results analysis, it was observed that HGSSA obtained the highest NPF with the lowest MID index. This algorithm has solved different sample problems in an average of 213.97 seconds. As a result, the efficiency of this method has been proven.

For future research, it is suggested to address environmental aspects along with economic and social aspects. It is also suggested to use the robust method to control the parameters of the model due to its higher efficiency. Finally, linearization of the model and the use of exact methods can provide more acceptable results.

Conflicts of Interest

All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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Ghahremani-Nahr et al.| J. Appl. Res. Ind. Eng. 10(4) (2023) 518-540