Scientia Iranica (2024) 31(22), 2166-2180

Sharif University of Technology
Scientia Iranica
Transactions E: Industrial Engineering
https://scientiairanica.sharif.edu

Research Note

Green design of regional wheat supply chains under uncertainty

Reza Babazadeh * and Meisam Shamsi

Faculty of Engineering, Urmia University, Urmia, West Azerbaijan Province, Iran.

* Corresponding author: r.babazadeh@urmia.ac.ir (R. Babazadeh)

Received 12 July 2020; received in revised form 13 April 2022; accepted 29 May 2022

Keywords

Wheat supply chain;
Optimization;
Fuzzy mathematical programming;
Uncertainty;
Wheat swap and export.

Abstract

This study presents a fuzzy mathematical programming model to optimize regional wheat hub center in Iran with the aim of achieving green fulfillment of domestic demand, swap and export of wheat to neighboring countries. The proposed model is developed for a 10-year planning horizon with real-world assumptions under uncertainty. By the proposed model, the optimal decisions are made on the amount of wheat cultivation areas in different provinces, capacity of silos, amount of import, swap and export of wheat, transportation mode and storage amount of wheat in different periods. Two objective functions including economic and environmental goals are optimized by the proposed model. The proposed model is examined under uncertainty conditions and the possibilistic programming approach is used to deal with the uncertainty of parameters. Finally, the presented model is validated through investigating a real case study in Iran. The results show the efficiency of the model for making optimal strategic and tactical decisions in wheat supply chains.

1. Introduction

Wheat is one of the most important crops that plays a major role in providing food to the community and can be grown in most arid and semi-arid areas. Wheat is sown throughout the world in different seasons, and every month, wheat is harvested in one part of the world. Wheat makes up 15% to 18% of the world's food consumption, and in Iran it supplies about 47% of the calories consumed per person per day [1].

According to FAO statistics, Iran produced 14 million tons of wheat in 2013, 3.7% increase over the previous year [2]. Over the past 52 years, the country's wheat production shows that in some years the production has increased by up to 70% and in some years the production of wheat has decreased by up to 50%. One of Iran's major challenges in this area is achieving fulfillment of domestic demand and exporting it to regional countries. Depending on the geographical location of Iran, it can play the role of cereal hub between several countries. In this case, the export, transit and swap of wheat through Iran will be possible with very low costs. Iran is seeking to become a grain hub to achieve better economic conditions through the construction of more silos, more wheat production and wheat-derived foods.

Despite Iran's excellent potential to become a regional wheat trading hub, it is still recognized as one of the wheat importing countries and annually allocates a significant share of oil currencies to wheat imports. According to a feasibility study conducted in Government Trading Corporation [1], Iran has a strategic position to become a wheat trading center in the region and can capture a major share of the wheat consumption markets in the regional countries. Iran's strategic position requires it to deliver wheat to the Persian Gulf States at a lower cost. Therefore, wheat exporting countries such as Russia, Ukraine, and Kazakhstan in northern Iran, are interested in delivering wheat through Iran rather than long sea shipping.

In Iran, wheat cultivation areas could be expanded so that the diversity of the two other major crops, barley and rice, can also be observed. Also, by gradually converting the areas under rain-fed farming, which accounts for 70% of the wheat cultivation area, to the irrigated area, the crop yield will be doubled. Therefore, proper planning to determine the optimal areas of wheat cultivation as well as the location and capacity of the silos will have a significant impact on the fulfillment of domestic demand and its trade in Iran.

At the following, the recent papers studying Supply Chain (SC) network optimization problem is reviewed. We have focused mainly on studies in the field of wheat SC optimization.

Djuric and Götz [3] studied the combination of price transmission and gross margin analysis at the wheat-to-bread SC. According to their results, the effects of export restrictions on the final consumer price of bread and consequently food price inflation, strongly depend on the price behavior of intermediaries. Gholamian and Taghanzadeh [4] proposed a model for designing a wheat SC network that includes long-term supplier selection

To cite this article:
R. Babazadeh and M. Shamsi "Green design of regional wheat supply chains under uncertainty", Scientia Iranica (2024), 31(22), pp. 2166-2180. https://doi.org/10.24200/sci.2022.56383.4702

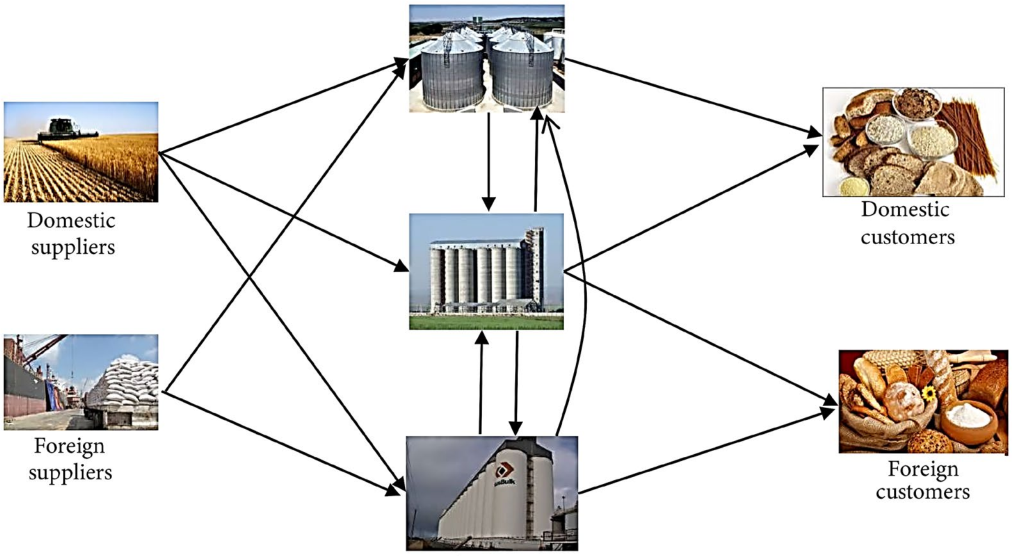

Figure 1. Wheat supply chain network.

decisions, location of new silos and medium-term decisions on the allocation and distribution of wheat. In their model the total costs, including fixed costs of supplier selection and warehouse location, purchase costs, transportation and inventory cost are considered. Hosseini-Motlagh et al. [5] developed a multi-objective model to design wheat SC network under uncertainty. They considered SC network including suppliers, silos, flour factories, and demand zones. They considered social impact and resilience dimensions in SC modeling. They proposed a hybrid stochastic fuzzy-robust programming approach to deal with the uncertainty of the problem. Pourmohammadi et al. [6] presented a Mixed Integer Linear Programming (MILP) model for integrated planning of wheat SC. Their model determines the optimal values for the decisions such as supplier selection, order planning, transportation, storage and distribution under uncertainty. Their model focuses on wheat quality and sleep period. They proposed a fuzzy chance-based solution approach to deal with uncertainties of the model. Trisna et al. [7] developed a fuzzy multi-objective model to design the wheat flour SC network. In their model total costs are minimized and minimize the total cost and product quality, reliability, and local flour usage are maximized. The model is a mixed integer non-linear programming one and is solved by non-dominated sorting genetic algorithm. Naderi et al. [8] developed a MILP model to design the wheat distribution network in Iran. They developed a logic-based Benders decomposition algorithm to solve the model for large sizes. The results showed that the proposed solution method is efficient in terms of achieving optimality and solution time. Motevalli-Taher et al. [9] presented a multi-objective mathematical model to optimize sustainable wheat SC. Their model minimizes total costs and water consumption and maximizes job opportunities. They used a simulation method to handle the demand uncertainty. Stanco et al. [10] presented a theoretical framework of the sustainable innovation processes visualized at the SC. Sustainable collective innovation needs the participation of all partners in the wheat SC. Dossa et al. [11] used dimensions of transaction cost economics to investigate the effect of transactions in the circulation of circular economy in wheat SC in British. They showed that financial considerations are the main component driving circular economic adoption. However, transaction act as an indirect driver to circular economic adoption. Deng et al. [12] improved the environmental and economical sustainability of wheat SC through analyzing the performance of all stakeholders. According to their results, 77% of GHG is emitted in wheat cultivation and less than 8% of the total economic benefits is achieved in this stage.

This study presents a fuzzy mathematical programming model to optimize tactical and strategic decisions in wheat SC net-work. Green development goals in SC network design are considered. To this end, a multi-period planning model is presented for a 10-year planning horizon with real-world assumptions under uncertainty. The proposed model determines the optimal amount of wheat cultivation areas, capacity of silos, amount of import, swap and export of wheat, transportation mode and storage amount of wheat in different periods. Two objective functions including economic and environmental objectives are considered in the proposed model. To deal with the uncertainty of the problem, a possibilistic programming method based on mean and absolute deviation of fuzzy numbers is used. To verify and validate the performance of the proposed model, a real case study is conducted in Iran.

The structure of the paper is organized as follows. In Section 2, the proposed model for optimizing wheat SC network and creating wheat hub center is described. In Section 3, the proposed model is implemented in a real case in Iran and an efficient solution method is developed. Finally, Section 4 presents the conclusions and managerial implications and opens some future research directions.

2. Proposed model

In some provinces of Iran, wheat production exceeds demand, so surplus wheat is either transferred to other provinces or stored for future use. The imbalance between wheat production and consumption in different provinces in different periods requires a wheat SC management system. Storage capacity in some provinces of the country is less than required, while in other provinces overcapacity is available. Also, Iran enjoys the privileged position of delivering wheat from the northern exporting countries to the Southern Gulf States. In other words, Iran has a strategic position to become a wheat hub center. Therefore, a mathematical programming model is developed in this section with the aim of optimizing strategic and tactical decisions related to the wheat SC in Iran. Figure 1 shows the supply chain of the wheat under investigation. As can be seen, the wheat is supplied either from domestic or foreign suppliers and then transported to silo centers. Domestic and foreign customers' demand is met by wheat stored in silo centers. Wheat transport within the SC is done by road and rail transportation modes. It is also possible to transport laterally (transshipment) between different silos whose values are determined by the proposed model. Side transportation between silos is considered because in some cases, supplying wheat from the extra supply of lateral silos may be less costly than supplying wheat from foreign or domestic suppliers.

The assumptions considered in the development of the proposed model include:

- The planning horizon is 10 years and each period is considered as one year;
- All wheat cultivation areas and also capacity of silos in one province are aggregated and each province is considered as a node of the wheat SC network. This assumption is made to reduce the complexity of the problem;
- There are two types of domestic and foreign customers;
- Demand shortage for domestic and foreign customers is not allowed;
- Lateral transshipment between silos is allowed;
- Safety stock is maintained in each province;
- Demand of wheat and other economic and technological parameters are considered to be uncertain;
- Wheat transportation is performed using two modes: road and rail;
- FIFO storage approach is assumed to hold wheat in silos. Wheat could be stored at most three years in silos.

The used indices, parameters and decision variables of the proposed model are defined as follows:

Sets

F Set of wheat cultivation areas (domestic supplier) ($f = 1,\ldots, F$)

S Set of silos ($s, s' = 1,\ldots, S$)

I Set of foreign suppliers ($i=1,\ldots, I$)

K Set of domestic customers ($k=1,\ldots, K$)

J Set of foreign customers ($j=1,\ldots, J$)

L Set of transportation mode ($l=1,\ldots, L$)

T Set of time period ($t=1,\ldots, T$)

IE Set of silos used for wheat import and export

NIE Set of silos used only for wheat storage to meet domestic demand

Technical parameters

D_{kt} Demand of domestic customer k in period t

DE_{jt} Demand of foreign customer j in period t

FWD_f Current rain-fed cultivation area in province f

FWA_f Current irrigated cultivation area in province f

FCS_s Current capacity of silo in province s

UW_f Maximum available area in province f could be allocated for wheat cultivation

US_s Maximum installable capacity of silo in province s due to budget limitation

α_f Wheat harvest rate per hectare of rain-fed farms in province f

β_f Wheat harvest rate per hectare of irrigated farms in province f

SS_{st} Amount of wheat safety stock in province s in period t

Dis_{fls} Distance between wheat farms in province f and silo in province s by transportation mode l

$Dis_{sls'}$ Distance between silo in province s and silo in province s' by transportation mode l

Dis_{slk} Distance between silo in province s and domestic customer k by transportation mode l

Economic parameters

ECW_{ft} Cost of increasing per hectare of rain-fed farms in province f in period t

ECA_{ft} Cost of increasing per hectare of irrigated farms in province f in period t

ECS_{st} Cost of adding one ton capacity for silo in province s in period t

PCW_{ft} Wheat production cost in rain-fed farms in province f in period t

PCA_{ft} Wheat production cost in irrigated farms in province f in period t

HC_{st} Inventory cost of storing wheat in silo in province s in period t

KC_{ist} Purchasing and transportation cost of wheat from foreign supplier i to silo s in period t

$TC1_{flst}$ Transportation cost of wheat from province f to silo s by transportation mode l in period t

$TC2_{sls't}$ Transshipment cost of wheat from silo s to silo s' by transportation mode l in period t

$TC3_{slkt}$ Transshipment cost of wheat from silo s to domestic customer k by transportation mode l in period t

PX_{sjt} Income due to wheat export from silo s to foreign customer j in period t

Environmental impact parameters

EnD_f Environmental impact of rain-fed wheat cultivation per hectare in province f

EnA_f Environmental impact of irrigated wheat cultivation per hectare in province f

ω_1 Environmental impact of adding one ton capacity for silos

ω_2	Environmental impact of storage per ton of wheat in silos
ω_3	Environmental impact of wheat shipment per ton from foreign suppliers
ω_4	Environmental impact of wheat transportation per ton per kilometer
ω_5	Environmental impact of wheat export per ton

Decision variables

EWD_{ft}	Optimal amount of extension of rain-fed farms of province *f* in period *t*
EWA_{ft}	Optimal amount of extension of irrigated farms of province *f* in period *t*
ES_{st}	Optimal amount of capacity extension of silos in province *s* in period *t*
SES_{st}	Total capacity expansion of silos in province *s* in period *t*
HW_{st}	Optimal inventory level in silo of province *s* in period *t*
KW_{ist}	Optimal amount of wheat purchased from foreign supplier *i* and transported to silo *s* in period *t*
TW_{flst}	Optimal amount of wheat transported from farms of province *f* to silos of province *s* by transportation model *l* in period *t*
$TD_{sls't}$	Optimal amount of wheat transshipped from silos of province *s* to silos of province *s'* by transportation model *l* in period *t*
TM_{slkt}	Optimal amount of wheat transported from silos of province *s* to domestic customer *k* by transportation model *l* in period *t*
EX_{sjt}	Optimal amount of wheat export from silos of province *s* to foreign customer *j* in period *t*

According to defined nomenclatures, the mathematical model is developed as follows:

$$\begin{aligned}\text{Min } Z_1 = &\textstyle\sum_f\sum_t ECW_{ft}EWD_{ft}\\ &+\textstyle\sum_f\sum_t ECA_{ft}EWA_{ft}\\ &+\textstyle\sum_s\sum_t ECS_{st}ES_{st}\\ &+\textstyle\sum_f\sum_t PCW_{ft}\alpha_f(FWD_f+EWD_{ft})\\ &+\textstyle\sum_f\sum_t PCA_{ft}\beta_f(FWA_f+EWA_{ft})\\ &+\textstyle\sum_s\sum_t HC_{st}HW_{st}\\ &+\textstyle\sum_i\sum_s\sum_t KC_{ist}KW_{ist}\\ &+\textstyle\sum_f\sum_l\sum_s\sum_t TC1_{flst}TW_{flst}\\ &+\textstyle\sum_s\sum_l\sum_k\sum_t TC3_{slkt}TM_{slkt}\\ &+\textstyle\sum_s\sum_l\sum_{s'\neq s}\sum_t TC2_{sls't}TD_{sls't}\\ &-\textstyle\sum_s\sum_j\sum_t PX_{sjt}EX_{sjt},\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Min } Z_2 = &\textstyle\sum_f\sum_t EnD_f.(FWD_f+EWD_{ft})\\ &+\textstyle\sum_f\sum_t EnA_f.(FWA_f+EWA_{ft})\\ &+\textstyle\sum_s\sum_t\omega_1 ES_{st}+\sum_s\sum_t\omega_2 HW_{st}\\ &+\textstyle\sum_i\sum_s\sum_t\omega_3 KW_{ist}\\ &+\textstyle\sum_f\sum_l\sum_s\sum_t\omega_4 Dis_{flst}.TW_{flst}\\ &+\textstyle\sum_s\sum_l\sum_{s'}\sum_t\omega_4 Dis_{sls't}.TD_{sls't}\\ &+\textstyle\sum_s\sum_l\sum_k\sum_t\omega_4 Dis_{slkt}.TM_{slkt}\\ &+\textstyle\sum_s\sum_j\sum_t\omega_5 EX_{sjt},\end{aligned} \tag{2}$$

$$\sum_s\sum_l TM_{slkt}=D_{kt} \qquad \forall k,t \tag{3}$$

$$\textstyle\sum_s EX_{sjt}=DE_{jt} \qquad \forall j,t \tag{4}$$

$$\begin{aligned}\textstyle\sum_l\sum_s TW_{flst}=&\,\alpha_f(FWD_f+EWD_{ft})\\ &+\beta_f(FWA_f+EWA_{ft}) \quad \forall f,t\end{aligned} \tag{5}$$

$$\begin{aligned}HW_{st}=&\,HW_{s,t-1}+\sum_f\sum_l TW_{flst}\\ &+\textstyle\sum_{s'\neq s}\sum_l TD_{s'lst}-\sum_{s\neq s'}\sum_l TD_{sls't}\\ &-\textstyle\sum_l\sum_k TM_{slkt} \qquad \forall s\in NIE,t\end{aligned} \tag{6}$$

$$\begin{aligned}HW_{st}=&\,HW_{s,t-1}+\sum_f\sum_l TW_{flst}\\ &+\textstyle\sum_{s'\neq s}\sum_l TD_{s'lst}\\ &+\textstyle\sum_i KW_{ist}-\sum_{s\neq s'}\sum_l TD_{sls't}\\ &-\sum_l\sum_k TM_{slkt}-\sum_j EX_{sjt} \quad \forall s\\ &\in IE,t\end{aligned} \tag{7}$$

$$HW_{st}\geq SS_{st} \qquad \forall s,t \tag{8}$$

$$\begin{aligned}&FWD_f+FWA_f+\sum_t EWD_{ft}\\ &+\textstyle\sum_t EWA_{ft}\leq UW_f \qquad \forall f\end{aligned} \tag{9}$$

$$SES_{st}=SES_{s,t-1}+ES_{st} \qquad \forall s,t \tag{10}$$

$$HW_{st}\leq FCS_s+SES_{st} \qquad \forall s,t \tag{11}$$

$$FCS_s+SES_{st}\leq US_s \qquad \forall s,t \tag{12}$$

All variables are continuous and non-negative. (13)

The proposed model consists of two objective functions: the economic objective function including minimizing the costs of the whole SC and the environmental objective function minimizing the environmental impacts of the SC processes. Objective function (1) includes development costs of rain-fed and irrigated wheat farms, cost of capacity expansion of silos, wheat production and harvesting costs of rain-fed and irrigated farms, wheat holding cost in silos, wheat importing cost from foreign suppliers, wheat transportation costs between different layers, wheat transshipment costs between silos, income from export and swap of wheat. Due to minimizing the objective function, the income is extracted from total costs.

Objective function (2) minimizes total environmental impact of all processes of the wheat SC network. These processes in the considered SC include wheat cultivation in rain-fed and irrigated farms, wheat production and harvesting, capacity expansion of silos, wheat storage, wheat import, wheat transportation and transshipment, and wheat export. Constraint (3) guarantees that all domestic demand is met through domestic production and import of wheat. Constraint (4) implies that all foreign demand for wheat is satisfied through export or swap of wheat. It should be noted that certain amount of demand of neighboring countries are satisfied through Iran. Constraint (5) express that all produced wheat from rain-fed and irrigated farms is transported to silos by road and rail transportation modes. Restriction (6) states that the amount of wheat in domestic silos in current period is equal to the amount of wheat left over from the previous period, plus the amount of wheat shipped from the farms to the silo, plus the amount of wheat that is transshipped from lateral silos to the silo in the current period, minus the amount of wheat that is transshipped from the silo to other silos, minus the amount of wheat sent from the silo to domestic customers. Restriction (7) is the same as restriction (6), except that it reflects the balance of inventory in import-export silos. In other words, the amount of import and export are added to restriction (6). Constraint (8) states that safety stock in silos should be maintained according to the needs of each province. Constraint (9) indicates the maximum amount of agricultural land available for allocation to rain-fed and irrigation farms in each province. Constraint (10) calculates the total capacity expansion for each silo. This is equal to the amount of capacity development in the previous period plus the amount of capacity development in the current period. Constraint (11) states that the amount of wheat storage in each silo cannot exceed the total capacity of that silo. The total capacity is equal to the current capacity of the silos in each province plus the total capacity development in that province. Constraint (12) states that the total current capacity and capacity development of silos cannot exceed a certain level in a province. Also, all variables of the proposed model are nonnegative continuous variables. Since the proposed model is a linear programming model, it will be solved in a good solution time.

The uncertainty of parameters has a significant impact on the performance of SC [13]. This effect is intensified in wheat SC due to involvement of its parameters with uncertainty [14]. In a wheat supply chain, the main parameters such as wheat yield, demand, transportation costs, operational costs, inventory costs, and price are subject to uncertainty. Therefore, it is necessary to consider the uncertainty of parameters in modeling wheat SC. To model the uncertainty, the behavior of uncertainty should be recognized. In cases where there is sufficient historical data and a probability distribution can be made for the data, probability theory-based approaches are used to optimize under uncertainty conditions [15]. However, in many real-world applications, such as the considered case study, there is not sufficient historical data to recognize the probability distribution of uncertain parameters. In such conditions, limited historical data and knowledge of experts are used to make possibility distribution of uncertain parameters [16]. In this research, the novel approach based on possibilistic programming is used to deal with the uncertainty of parameters.

3. Solution method and Implementation results

In this section, firstly a two-step solution approach is presented. In the first step, the objective functions and constraints are converted to their equivalent deterministic forms. In the second step, a combined lexicographic and augmented ε-constraint method are used to find the optimal Pareto solution set. Then, the case study and data gathering scheme are described and the achieved results are presented.

3.1. Solution method

In this subsection firstly, the proposed possibilistic programming model is converted to its equivalent deterministic model. Then, the a combined lexicographic and augmented ε-constraint method is used to handle the multiple objectives of the pro-posed model.

3.1.1. The equivalent deterministic model

According to recent advances in possibilistic programming methods, we utilize the approach called possibilistic mean-absolute deviation model [17], that optimizes mean and risk values of objective function under uncertainty, simultaneously. This approach guarantees that robust solution is achieved for the wheat SC network [18].

In the proposed model, both economic and environmental objective functions have been tainted with uncertainty. In this paper, the possibilistic programming model is developed by integrating the mean and standard deviation of the fuzzy objective function. The standard deviation of the objective functions is also considered as the risk factor. The possibility distribution of fuzzy parameters is assumed to be triangular form. The proposed possibilistic programming model can be shown as follows, that there are uncertain parameters in both the objective function and the constraints [17].

$$\begin{aligned} &\text{Min } Z = \bar{M}(\tilde{c}x) + \gamma|\sigma(\tilde{c}x)| \\ &\text{s.t.:} \quad \tilde{a}_i x \geq \tilde{b}_i \quad i = 1, \ldots, l \\ &\qquad \tilde{a}_i x = \tilde{b}_i \quad i = l+1, \ldots, m \\ &\qquad\qquad x \geq 0 \end{aligned} \tag{16}$$

The above model (16) is based on the mean and standard deviation of fuzzy numbers. The first statement in the objective function minimizes the mean and the second minimizes the standard deviation of fuzzy objective function. The multi-criteria decision-making method can be used to determine the value of γ (risk coefficient) in order to strike a balance between the mean of the objective function and the absolute deviation of the objective function. The above model enables the decision maker to consider the risk aspects in addition to considering the average conditions. To convert the proposed possibilistic model to an equivalent deterministic model, suppose $\tilde{c}$ is an uncertain parameter whose value is expressed by a triangular fuzzy number. The possibility distribution of the triangular fuzzy number $\tilde{c}$ is determined by three points. For example, $\tilde{c} = (c^p, c^m, c^o)$ is a triangular fuzzy number in which c^p is the most pessimistic value, c^m is the most possible value, and c^o is the most optimistic value. These values are determined by available data and expert opinions. The membership function of fuzzy number $\tilde{c}$ is defined as follows:

$$\mu_{\tilde{c}}(x) = \begin{cases} 0 & \text{if} \quad x \in (-\infty, c^p] \\ f_c(x) = \dfrac{x - c^p}{c^m - c^p} & \text{if} \quad x \in [c^p, c^m] \\ 1 & \text{if} \quad x = c^m \\ g_c(x) = \dfrac{c^0 - x}{c^0 - c^m} & \text{if} \quad x \in [c^m, c^0] \\ 0 & \text{if} \quad x \in [c^0, +\infty) \end{cases} \tag{17}$$

According to the principles of mean and absolute deviation of a fuzzy number, and also the principles of fuzzy mathematical programming, the equivalent deterministic model could be written as follows. For more details, interested readers may refer to [16].

$$\text{Min } z = (\tfrac{c^p+4c^m+c^o}{6})x + \gamma(\tfrac{c^o-c^p}{3})x$$

s. t.:

$$[(1-\alpha)(\tfrac{2}{3}a^m + \tfrac{1}{3}a^o) + \alpha(\tfrac{2}{3}a^m + \tfrac{1}{3}a^p)]x$$
$$\geq (1-\alpha)\left(\frac{2}{3}b^m + \frac{1}{3}b^p\right) + \alpha\left(\frac{2}{3}b^m + \frac{1}{3}b^o\right)$$
$$i = 1, \dots, l$$
$$[(1-\tfrac{\alpha}{2})(\tfrac{2}{3}a^m + \tfrac{1}{3}a^o) + \tfrac{\alpha}{2}(\tfrac{2}{3}a^m + \tfrac{1}{3}a^p)]x$$
$$\geq \left(1-\frac{\alpha}{2}\right)\left(\frac{2}{3}b^m + \frac{1}{3}b^p\right) + \frac{\alpha}{2}\left(\frac{2}{3}b^m + \frac{1}{3}b^o\right)$$
$$i = l+1, \dots, m$$
$$[(\tfrac{\alpha}{2})(\tfrac{2}{3}a^m + \tfrac{1}{3}a^o) + (1-\tfrac{\alpha}{2})(\tfrac{2}{3}a^m + \tfrac{1}{3}a^p)]x \quad (18)$$
$$\leq \left(1-\frac{\alpha}{2}\right)\left(\frac{2}{3}b^m + \frac{1}{3}b^p\right) + \frac{\alpha}{2}\left(\frac{2}{3}b^m + \frac{1}{3}b^o\right)$$
$$i = l+1, \dots, m \qquad x \geq 0$$

3.1.2. Handling multiple objective functions

The ε-constraint method is one of the most popular posteriori methods in which the Pareto-optimal set is achieved through changing the ε-vectors of objectives considered as constraints and solving their corresponding single objective problems [19]. The augmented ε-constraint method could explore more efficient solution from the optimal Pareto set [17].

Without loss of generality, consider p objective functions (OFs) of the MOP which should be minimized. The ε-constraint method optimizes the main OF (for example, f_l) subject to the feasibility constraints and constrained objectives and is stated as follows [20]:

$$\text{Min}\{f_1(x) | x \in X \wedge f_i(x) \leq \varepsilon_i, \quad i = 2, \dots, p\}, \qquad (19)$$

where x is the vector of decision variables and X represents the feasible decision space. The problem (19) is a single objective problem and can be conveniently solved for different ε-vectors and the DM can select the most preferred solution among the efficient set. To generate different ε-vectors, firstly the positive ideal solution (f^{PIS}) and negative ideal solution (f^{NIS}) for each objective function is achieved using flexible lexicographic method illustrated in Algorithm 1 [21].

Algorithm 1.

$i = 1$

While $i \leq p$

$f_i^{PIS} = \text{Min } \{f_i(x) | x \in X\}$

j=1

for j=1 to p and $j \neq i$

$f_j(\hat{x}_{ji}) =$

$\text{Min}\{f_j(x) | x \in X \wedge f_i(x)$

$\leq f_i^{PIS} + (1-\alpha 1)(q_i f_i^{PIS})\}$

$i = i + 1$

End while.

$f_i^{PIS} = f_i(x_i'), i = 1, \dots, p,$ where

$x_i' = \arg\ (\text{Min } \{f_i(x) | x \in X\})$

Parameter $\alpha 1$ is a satisfaction degree of violation of OFs from their optimal values (f^{PIS}) by q percent. Then, the ranges of constrained p-1 objectives are divided into a number of intervals based on some grid points using Eq. (20):

$$\varepsilon_i = f_i^{NIS} - \left(\frac{f_i^{NIS} - f_i^{PIS}}{m}\right) \times n, \qquad (20)$$
$$n = 0, 1, 2, \dots, m$$

After calculating the ε-vectors, the augmented ε-constraint approach is applied as follows [22]:

$$\text{Min}\{f_1(x) - (r_1 \times \sum_{i=2}^{p} \frac{s_i}{r_i}) | x \in X \wedge f_i(x) + s_i = \varepsilon_i \wedge s_i \in R^+, i = 2, \dots, p\} \qquad (21)$$

Where r_i is the range of objective ith and is calculated as $r_i = f_i^{NIS} - f_i^{PIS}$.

3.2. Implementation and results

Iran's privileged position in the middle of wheat supplying and consuming countries has made it possible for Iran to become a regional hub of grain. In this regard, the conversion of Iran into a regional hub or cereal trade hub will allow exporters to gain greater market share, the importers gain lower cost, and provide Iran with economic growth advantage.

The parameters such as the area of rain-fed and irrigated land for wheat cultivation, cultivation costs of wheat in rain-fed and irrigated farms in different provinces, yield per hectare of rain-fed and irrigated farms in different locations were obtained from the Jihad Agricultural Data System. All this data is available at www.dbagri.maj.ir/zrt /.

To calculate transportation costs for each transportation mode, firstly the real distance between two points was gathered from the Ministry of Roads & Urban Development (www.mrud.ir). Then, unit transportation cost is achieved through investigating the prices of wheat transport companies in Iran. To calculate the environmental impacts, the amount of carbon dioxide emitted by various processes is calculated using the well-known Eco-indicator 99 method by SimaPro 8 software. SimaPro software is the most comprehensive software for calculating the environmental impact of various processes (www.pre-sustainability.com).

Demand for wheat is predicted for 10 years planning horizon according to Per capita consumption of wheat and population of each province (www.amar.org.ir). Demand for different provinces has been shown in Table 1. Wheat consumption for 90 days in each province is considered as a safety stock for that province. It should be noted that due to space limitation only the most possibilistic values are shown in Table 1.

Demand of neighboring countries of Iran, is achieved through the website www.indexmundi.com provided by FAO. It is assumed that Iran can meet 30% of wheat demand in neighboring countries in the planning horizon. Accordingly, Table 2 illustrate the amount of wheat demand that Iran should plan to satisfy them in the planning horizon. Table 3 indicates the amount of current capacity of silos, current rain-fed cultivation areas, and current irrigated cultivation areas for each province (www.dbagri.maj.ir/zrt/). It is worth noting that only the capacity of metal and concrete silos is listed in the Table 3 and the capacity of open warehouses is not included. In Gilan province all wheat farms are irrigated lands due to availability of water resources. Also, in some provinces like as Alborz wheat farms are cultivated in rain-fed form due to water supply limitations.

Table 4 shows the optimal amount of extension of rain-fed cultivation farms in each period. For example, the West Azerbaijan and Ardabil provinces do not need to develop wheat cultivation fields in any period, but for Ilam province, the first and second periods of development are intended for rain-fed wheat cultivation. Also, according to the results, none of the provinces need to develop irrigated wheat fields. This observation could be justified due to geographical location of Iran in arid and semi-arid region and severe water shortage for development of irrigated agriculture. Also, extension of irrigated cultivation areas needs more costs respect to rain-fed cultivation farms. The results of Table 4 confirm that Iran could meet the domestic and foreign wheat demand through extension of rain-fed cultivation farms.

Table 1. Predicted demand of wheat for different provinces of Iran *(t/y)*.

	Period									
Province	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
East Azerbaijan	738558	743796	748646	753954	759299	764683	770104	775565	781063	786601
West Azerbaijan	620994	628948	637096	641613	646162	650743	655357	660004	664683	669396
Ardabil	247544	249290	251036	252816	254608	256413	258231	260062	261906	263763
Isfahan	971358	979700	987654	994656	1001709	1008811	1015963	1023166	1030421	1037726
Alborz	526206	529889	533598	537334	541095	544883	548697	552538	556405	560300
Ilam	111550	112714	113878	114685	115499	116317	117142	117973	118809	119651
Bushehr	213400	217862	222324	223900	225488	227086	228696	230318	231951	233595
Tehran	2930758	2963932	2997300	3018551	3039952	3061506	3083212	3105072	3127087	3149258
Chahar M.	179062	181002	182748	184044	185349	186663	187986	189319	190661	192013
Khorasan J.	147440	149186	151126	152197	153277	154363	155458	156560	157670	158788
Khorasan R.	1214828	1232482	1250330	1259195	1268123	1277114	1286168	1295287	1304471	1313719
Khoan Sh.	174406	176346	178286	179550	180823	182105	183396	184696	186006	187325
Khozestan	916456	929066	941482	948157	954880	961650	968468	975334	982249	989213
Zanjan	203118	205252	207192	208661	210140	211630	213131	214642	216164	217696
Semnan	128428	130562	132696	133637	134584	135539	136499	137467	138442	139423
Sistan va	528456	541454	554646	558578	562539	566527	570544	574589	578663	582766
Fars	918590	927708	936632	943273	949961	956696	963479	970310	977189	984118
Gazvin	240172	242500	244828	246564	248312	250073	251846	253631	255429	257240
Gom	235516	239590	243470	245196	246935	248685	250449	252224	254013	255813
Kurdistan	295656	297790	299536	301660	303798	305952	308122	310306	312506	314722
Kerman	595774	604698	613622	617973	622354	626766	631210	635686	640193	644732
Kermanshah	382180	383538	384702	387430	390176	392943	395729	398534	401360	404206
Kohgiluyeh B.	134248	136382	138516	139498	140487	141483	142486	143497	144514	145539
Golestan	362974	369182	375390	378052	380732	383431	386150	388888	391645	394422
Gilan	490238	493342	496640	500161	503707	507279	510875	514497	518145	521819
Lorestan	349394	352304	355214	357732	360269	362823	365396	367986	370595	373223
Mazandaran	612070	617308	622546	626960	631405	635882	640390	644930	649503	654108
Markazi	282464	285180	288090	290133	292190	294261	296348	298449	300565	302696
Hormozgan	325144	331740	338530	340930	343347	345782	348233	350702	353189	355693
Hamadan	346484	348230	349782	352262	354759	357275	359808	362359	364928	367515
Yazd	206998	211266	215340	216867	218404	219953	221512	223083	224664	226257

Table 2. Predicted demand of wheat for neighboring countries of Iran *(t/y)*.

	Period									
Province	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Iraq	720	792	828	864	900	936	972	1008	1044	1080
Afghanistan	700	770	805	840	875	910	945	980	1015	1050
Emirates	360	396	414	432	450	468	486	504	522	540
Oman	140	154	161	168	175	182	189	196	203	210
Kuwait	100	110	115	120	125	130	135	140	145	150

Table 3. Current capacity of silos, rain-fed and irrigated cultivation areas for each province.

Province	**Capacity of silos (*t*)**	**Rain-fed cultivation areas (*ha*)**	**Irrigated cultivation areas (*ha*)**
East Azerbaijan	890000	82450	355000
West Azerbaijan	351000	88354	270250
Ardabil	284000	73200	247241
Isfahan	599000	52700	17200
Alborz	334000	10437	0
Ilam	250000	38000	80000
Bushehr	33000	16500	78500
Tehran	1102000	38960	1308
Chahar M.	115000	24200	37800
Khorasan J.	21000	22130	1000
Khorasan R.	983000	175090	125000
Khoan Sh.	230000	52448	104953
Khozestan	1018000	384000	151300
Zanjan	33000	19150	287280
Semnan	115000	25160	8500
Sistan B.	330000	70600	0
Fars	632000	248000	95000
Gazvin	334000	47908	92980
Gom	449000	6012	1250
Kurdistan	326000	33200	521400
Kerman	899000	44000	0
Kermanshah	785000	97000	314000
Kohgiluyeh B.	115000	24100	82350
Golestan	718000	159688	220311
Gilan	430000	0	13856
Lorestan	689000	57693	197109
Mazandaran	430000	37550	29080
Markazi	171000	57000	145250
Hormozgan	50000	13000	0
Hamadan	693000	80110	322820
Yazd	75000	12150	0

Table 5 determines the optimal capacity development of silos in each province. According to the results, only four provinces, and only in the first period, need to expand their wheat silos. Tables 6 and 7 show the optimal amount of rain-fed and irrigated wheat to be produced in each province in each period, respectively. Irrigated wheat is produced from current irrigated farms. After the wheat is harvested, the wheat is stored in silos. In each period, wheat storage in silos is according to the needs of each province as well as the export amount to other countries. The optimal amount of wheat storage in each period and in each province is presented in Table 8. In each period, wheat harvested from wheat farms is sent to the silos in both road and rail transportation modes. According to the results, mainly the mode of rail transport is chosen because of its lower cost and environmental impact. Also, some provinces prefer to supply the required wheat through transshipping wheat from other silos instead of importing from foreign countries or supplying from cultivation farms. Table 9 indicates the amount of wheat exported to neighboring countries.

Table 4. Optimal amount of extension of rain-fed cultivation farms (*ha*).

	Period									
Province	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
East Azerbaijan	84799	308	141	145	148	92	94	96	98	74
West Azerbaijan	0	0	0	0	0	0	0	0	0	0
Ardabil	0	0	0	0	0	0	0	0	0	0
Isfahan	18273	283	269	276	305	308	310	313	315	318
Alborz	0	0	0	0	0	0	0	0	0	0
Ilam	35376	24	0	0	0	0	0	0	0	0
Bushehr	23295	1318	513	520	527	534	540	548	349	355
Tehran	12080	0	0	0	0	0	0	0	0	0
Chahar M.	18529	71	0	0	0	0	0	0	0	0
Khorasan J.	3303	1096	308	310	313	316	319	322	325	328
Khorasan R.	84569	925	455	467	479	513	526	538	768	786
Khoan Sh.	30884	38	0	0	0	0	0	0	0	0
Khozestan	0	0	0	0	0	0	0	0	0	0
Zanjan	31	0	0	0	0	0	0	0	0	0
Semnan	6580	80	0	0	0	0	0	0	0	0
Sistan B.	11868	0	0	0	0	0	0	0	0	0
Fars	102900	0	0	0	0	0	0	0	0	0
Gazvin	33368	1957	1020	1037	1029	1085	1108	1132	530	0
Gom	0	0	0	0	0	0	0	0	739	1440
Kurdistan	166380	0	0	0	0	0	0	0	0	0
Kerman	0	0	0	0	0	0	0	0	0	0
Kermanshah	84506	0	0	0	0	0	0	0	0	0
Kohgiluyeh B.	0	0	0	0	0	0	0	0	0	0
Golestan	0	0	0	0	0	0	0	0	0	0
Gilan	0	0	0	0	0	0	0	0	0	0
Lorestan	0	0	0	0	0	0	0	0	0	0
Mazandaran	0	0	0	0	0	0	0	0	0	0
Markazi	60320	355	0	0	0	0	0	0	0	0
Hormozgan	0	0	0	0	0	0	0	0	0	0
Hamadan	0	0	0	0	0	0	0	0	0	0
Yazd	0	0	0	0	0	0	0	0	0	0

Table 5. Optimal amount of capacity expansion of silos (*t*).

Province	**Period**
	1
Bushehr	24843
Khorasan J.	18319
Zanjan	20906
Hormozgan	38077

Table 6. Optimal amount of rain-fed wheat production in each period (*t/y*).

Province	Period									
	1	2	3	4	5	6	7	8	9	10
East Azerbaijan	396609	1823	1042	1061	1076	816	826	835	845	729
West Azerbaijan	395	395	395	395	395	395	395	395	395	395
Ardabil	353	353	353	353	353	353	353	353	353	353
Isfahan	105731	1938	1854	1895	2064	2078	2093	2109	2123	2140
Alborz	66	66	66	66	66	66	66	66	66	66
Ilam	175643	308	188	188	188	188	188	188	188	188
Bushehr	103588	5932	2354	2384	2415	2445	2475	2508	1652	1652
Tehran	81726	263	263	263	263	263	263	263	263	263
Chahar M.	76137	391	99	99	99	99	99	99	99	99
Khorasan J.	10500	3531	1042	1050	1059	1067	1077	1085	1095	1104
Khorasan R.	391581	5083	2913	2969	3025	3180	3238	3296	4360	4439
Khoan sh.	132514	386	225	225	225	225	225	225	225	225
Khozestan	1890	1890	1890	1890	1890	1890	1890	1890	1890	1890
Zanjan	226	86	86	86	86	86	86	86	86	86
Semnan	32089	512	122	122	122	122	122	122	122	122
Sistan B.	31855	188	188	188	188	188	188	188	188	188
Fars	480794	1156	1156	1156	1156	1156	1156	1156	1156	1156
Gazvin	171895	10312	5492	5579	5540	5829	5948	6072	2971	246
Gom	25	25	25	25	25	25	25	25	3150	6108
Kurdistan	937844	187	187	187	187	187	187	187	187	187
Kerman	205	205	205	205	205	205	205	205	205	205
Kermanshah	471293	540	540	540	540	540	540	540	540	540
Kohgiluyeh B.	73	73	73	73	73	73	73	73	73	73
Golestan	700	700	700	700	700	700	700	700	700	700
Gilan	0	0	0	0	0	0	0	0	0	0
Lorestan	237	237	237	237	237	237	237	237	237	237
Mazandaran	136	136	136	136	136	136	136	136	136	136
Markazi	276947	1890	261	261	261	261	261	261	261	261
Hormozgan	65	65	65	65	65	65	65	65	65	65
Hamadan	400	400	400	400	400	400	400	400	400	400
Yazd	45	45	45	45	45	45	45	45	45	45

Table 7. Optimal amount of rain-fed wheat production in each period (*t/y*).

Province	**Period**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
East Azerbaijan	517	517	517	517	517	517	517	517	517	517
West Azerbaijan	461	461	461	461	461	461	461	461	461	461
Ardabil	485	485	485	485	485	485	485	485	485	485
Isfahan	18	18	18	18	18	18	18	18	18	18
Alborz	0	0	0	0	0	0	0	0	0	0
Ilam	163	163	163	163	163	163	163	163	163	163
Bushehr	77	77	77	77	77	77	77	77	77	77
Tehran	0	0	0	0	0	0	0	0	0	0
Chahar M.	38	38	38	38	38	38	38	38	38	38
Khorasan J.	0	0	0	0	0	0	0	0	0	0
Khorasan R.	185	185	185	185	185	185	185	185	185	185
Khoan sh.	146	146	146	146	146	146	146	146	146	146
Khozestan	198	198	198	198	198	198	198	198	198	198
Zanjan	342	342	342	342	342	342	342	342	342	342
Semnan	13	13	13	13	13	13	13	13	13	13
Sistan B.	0	0	0	0	0	0	0	0	0	0
Fars	100	100	100	100	100	100	100	100	100	100
Gazvin	139	139	139	139	139	139	139	139	139	139
Gom	0	0	0	0	0	0	0	0	0	0
Kurdistan	795	795	795	795	795	795	795	795	795	795
Kerman	0	0	0	0	0	0	0	0	0	0
Kermanshah	610	610	610	610	610	610	610	610	610	610
Kohgiluyeh B.	74	74	74	74	74	74	74	74	74	74
Golestan	772	772	772	772	772	772	772	772	772	772
Gilan	24	24	24	24	24	24	24	24	24	24
Lorestan	395	395	395	395	395	395	395	395	395	395
Mazandaran	66	66	66	66	66	66	66	66	66	66
Markazi	203	203	203	203	203	203	203	203	203	203
Hormozgan	0	0	0	0	0	0	0	0	0	0
Hamadan	362	362	362	362	362	362	362	362	362	362
Yazd	0	0	0	0	0	0	0	0	0	0

Table 8. Optimal amount wheat storage in different provinces (*t/y*).

Province	Period									
	1	2	3	4	5	6	7	8	9	10
East Azerbaijan	182882	184074	185379	186694	188017	189350	190693	192045	193407	194778
West Azerbaijan	154643	156647	157757	158876	160002	161137	162279	163430	164589	165755
Ardabil	61295	61724	62161	6202	63046	63493	63943	64397	64853	65313
Isfahan	240885	242841	244562	246296	248043	249801	251572	253356	255152	256961
Alborz	129381	130299	131223	131223	133090	134034	134984	135941	136905	137875
Ilam	27714	28000	28198	28398	28600	28802	29007	29212	29419	29628
Bushehr	53567	54664	55052	55442	55835	56231	56630	57031	57436	57834
Tehran	728761	736965	742190	747452	752752	758089	763464	768876	774328	779818
Chahar M.	44504	44933	45252	45573	45896	46221	46549	46879	47211	47546
Khorasan J.	36681	37158	37442	37687	37954	38223	38494	38767	39042	39319
Khorasan R.	303038	307427	309606	311801	314012	316238	318480	320738	323012	325303
Khoan sh.	43359	43836	44147	44460	44775	45093	45412	45734	46059	46385
Khozestan	228435	231488	233129	234782	236447	238123	239812	241512	243224	244949
Zanjan	50467	50944	51305	51669	52035	52404	52775	53150	53526	53906
Semnan	32102	32627	32858	33091	33326	33562	33800	34040	34281	34524
Sistan B.	133131	136374	137341	138315	139296	140283	141278	142279	143288	144304
Fars	228101	230296	231928	233573	235229	236897	238576	240268	241971	243687
Gazvin	59625	60197	60624	61054	61487	61923	62362	62804	63249	63698
Gom	58910	59864	60288	60715	61146	61579	62016	62456	62898	63344
Kurdistan	73220	73649	74171	74697	75226	75760	76297	76838	77383	77931
Kerman	148681	150875	151945	153022	154107	155200	156300	157408	158524	159648
Kermanshah	94303	94589	95260	95935	96615	97300	97990	98685	99385	100089
Kohgiluyeh B.	33533	34058	34299	34542	34787	35034	35282	35533	35784	36038
Golestan	90773	92300	92954	93613	94277	94945	95618	96296	96979	97666
Gilan	121301	122112	122978	123850	124728	125612	126503	127400	128303	129213
Lorestan	86623	87339	87958	88582	89210	89842	90479	91121	91767	92417
Mazandaran	151781	153069	154155	155248	156348	157457	158573	159697	160830	161970
Markazi	70119	70835	71337	71842	72352	72865	73381	73902	74426	74953
Hormozgan	81567	83237	83827	84421	85020	85622	86229	86841	87456	88077
Hamadan	85622	86003	86613	87227	87845	88468	89095	89727	90363	91004
Yazd	51945	52947	53322	53700	54081	54465	54851	55240	55631	56026

Table 9. Optimal export amount from different province to neighboring countries (*t/y*).

Origin	Destination	Period									
		1	2	3	4	5	6	7	8	9	10
Khorasan R.	Afghanistan	799	879	919	959	999	1039	1079	1119	1158	1198
Khozestan	Iraq	718	790	826	862	898	934	970	1006	1042	1078
Khozestan	Kuwait	115	126	132	138	144	149	155	161	167	172
Hormozgan	Emirates	424	467	488	509	530	551	573	594	615	636
Hormozgan	Oman	134	147	154	161	167	174	181	187	194	201

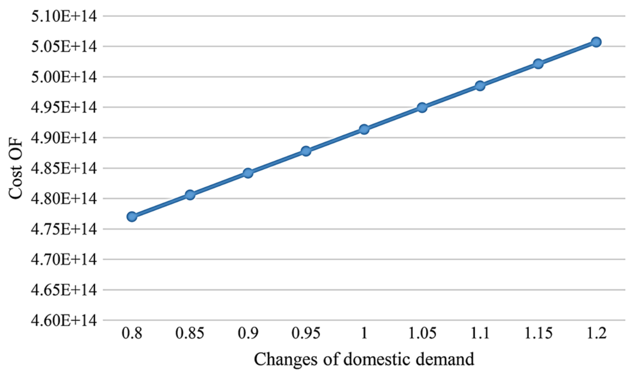

Figure 2. Changes of cost OF vs. domestic demand.

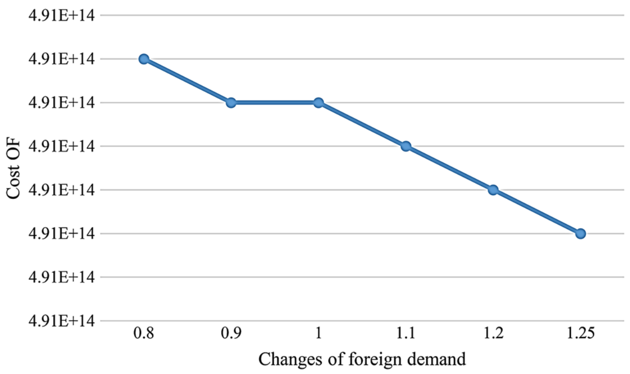

Figure 3. Changes of cost OF vs. foreign demand.

3.3. Sensitivity analysis

To verify and validate the proposed model, sensitivity analysis procedure is conducted on the most important parameters including domestic demand (D), foreign demand (DE), and transportation costs (TC). Domestic demand is changed in the range [0.8×D, 1.2×D]. Foreign demand is changed in the range [0.8×DE, 1.25×DE]. All transportation costs are simultaneously changed in the range [0.9×TC, 1.15×TC]. Economic objective function is optimized and the values of environmental objective function are calculated. Notably, due to high amount of environmental objective function (i.e., 3.94E+21), the small changes of this OF are not shown in outcome of GAMS. Therefore, we have not shown this OF in Figures 2-4.

Figure 2 illustrates that the cost OF is increased by increasing the domestic demand of wheat in a linear trend. That is the changes of domestic demand is an influencing parameter and should be more precisely considered when decisions are made. Figure 3 indicates the cost objective function is decreased by increasing the foreign demand of wheat. This shows that increasing the foreign demand of wheat leads to more profit of the SC and thus the total costs are decreased. Figure 4 shows that the total costs are increased when transportation costs are increased. This trend is changed in a linear form.

3.4. Policy implications

The achieved results help the policy makers to make optimal decisions in wheat SC. The policy implications withdrawn from this research include:

- Optimal decision making about rain-fed and irrigated cultivation areas of wheat; according to the achieved results the government can determine policies to encourage the wheat farmers to reach the optimal value of cultivation in specified areas. Policies such as

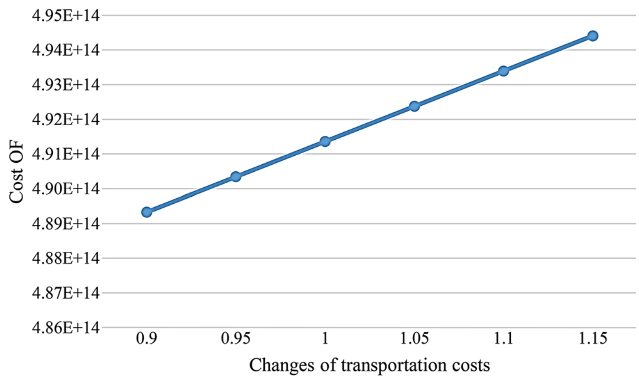

Figure 4. Changes of cost OF vs. transportation costs.

granting loan and guaranteed purchasing price are motivations in this field;

- Optimal decision making about establishing silos; according to the obtained results the government can encourage the investors and private sectors through giving low interest loans to invest in locations that need more capacity of silos;
- Optimal decision making about wheat import and export; based on the results the government could determine the optimal amount of import and export in each period and thus it could plan and give comprehensive program to importers and exporters to meet domestic and foreign demand;
- Optimal decision making about wheat flow among different locations using different transportation modes;
- Development rail transportation sector leads to improvement in transportation costs and environmental impacts. This issue plays a decisive role in turning Iran into a grain hub in the region;
- Wheat swap and lateral transshipment between silos could be improvement in transportation costs.

4. Conclusions

This research seeks to properly plan the wheat supply chain network in Iran with the aim of achieving green fulfillment of domestic demand, realization of swaps and export of wheat to neighboring countries. In this regard, a mathematical model is developed to optimize the strategic and tactical decisions of the wheat supply chain for a 10-year planning horizon with real-world assumptions. There are two economic and environmental objective functions. To calculate the environmental impact, the popular Eco-indicator 99 method is calculated using SimaPro 8 software. The combined lexicographic and augmented ε-constraint method is employed to handle the multiple objectives of the proposed model. The proposed model is examined under uncertainty of parameters and a new possibilistic programming method based on mean and absolute deviation of fuzzy numbers is used to deal with its uncertainty. Finally, the presented model is verified and validated through investigating a real case study. The results show the efficiency of the model for making optimal strategic and tactical decisions in the wheat supply chain. The proposed model determines the optimal decisions regarding the optimum level of wheat cultivation in the provinces, the optimal capacity of silos, the amount of import, export of wheat, and the optimal amount of wheat storage in different periods.

The achieved results confirm that Iran could be selected as the regional hub center for wheat trade. In this manner, the win-win approach in terms of low costs and environmental impact is achieved for all suppliers and consumers in the region. Also, through reasonable investment in rain-fed cultivation areas and capacity of silos, Iran could turn into a wheat hub center in the region.

For the future research direction, considering wheat quality and blending wheat with different quality are essential specially in swap and export processes. Also, construction time of silos may be addressed in future works. Developing efficient exact and heuristic solution approaches will help to solve the model for large size instances.

Acknowledgments

This work is based upon research funded by Iran National Science Foundation (INSF) under project No. 4001957. Also, the authors thank the anonymous referees for their valuable comments.

References

1. http://en.gtc-portal.com/
2. Statistics, A., Ministry of agriculture, Islamic Republic of Iran (2008).
3. Djuric, I. and Götz, L. "Export restrictions – Do consumers really benefit? The wheat-to-bread supply chain in Serbia", *Food Policy*, **63**, pp. 112-123 (2016). doi.org/10.1016/j.foodpol.2016.07.002
4. Gholamian, M.R. and Taghanzadeh, A.H. "Integrated network design of wheat supply chain: A real case of Iran", *Computers and Electronics in Agriculture*, **140**, pp. 139–147 (2017). doi.org/10.1016/j.compag.2017.05.038
5. Hosseini-Motlagh, S.M., Samani, M.R.G., and Abbasi Saadi, F. "A novel hybrid approach for synchronized development of sustainability and resiliency in the wheat network", *Computers and Electronics in Agriculture*, **168**, 105095 (2020). doi.org/10.1016/j.compag.2019.105095
6. Pourmohammadi, F., Teimoury, E., and Gholamian, M. "A fuzzy chance-constrained programming model for integrated planning of the wheat supply chain considering wheat quality and sleep period: a case study", *Scientia Iranica*, **29**(5), pp. 2593-2609 (2022). DOI: 10.24200/sci.2020.53772.3404
7. Trisna, T., Marimin, M., Arkeman, Y., et al. "Fuzzy multi-objective optimization for wheat flour supply chain considering raw material substitution", *International Journal of Industrial Engineering and Management*, **11**(3), pp. 180-191 (2021). doi.org/10.24867/IJIEM-2020-3-263
8. Naderi, B., Govindan, K., and Soleimani, H. "A Benders decomposition approach for a real case supply chain network design with capacity acquisition and transporter planning: wheat distribution network", *Annals of Operations Research*, **291**(1), pp. 685-705 (2020). doi.org/10.1007/s10479-019-03137-x
9. Motevalli-Taher, F., Paydar, M.M., and Emami, S. "Wheat sustainable supply chain network design with forecasted demand by simulation", *Computers and Electronics in Agriculture*, **178**, 105763 (2020). doi.org/10.1016/j.compag.2020.105763
10. Stanco, M., Nazzaro, C., Lerro, M., et al. "Sustainable collective innovation in the agri-food value chain: The case of the "Aureo" wheat supply chain", *Sustainability*, **12**(14), 5642 (2020). doi.org/10.3390/su12145642
11. Dossa, A.A., Gough, A., Batista, L., et al. "Diffusion of circular economy practices in the UK wheat food supply chain", *International Journal of Logistics Research and Applications*, **25**(3), pp. 328-347 (2022). doi.org/10.1080/13675567.2020.1837759
12. Deng, L., Zhang, H., Wang, C., et al. "Improving the sustainability of the wheat supply chain through multi-stakeholder engagement", *Journal of Cleaner Production*, **321**, 128837 (2021).

    doi.org/10.1016/j.jclepro.2021.128837
13. Govindan, K., Fattahi, M., and Keyvanshokooh, E. "Supply chain network design under uncertainty: A comprehensive review and future research directions", *European Journal of Operational Research*, **263**(1), pp. 108-141 (2017).

    doi.org/10.1016/j.ejor.2017.04.009
14. Anderson, E. and Monjardino, M. "Contract design in agriculture supply chains with random yield", *European Journal of Operational Research*, **277**(3), pp. 1072-1082 (2019). doi.org/10.1016/j.ejor.2019.03.041
15. Ghelichi, Z., Saidi-Mehrabad, M., and Pishvaee, M.S. "A stochastic programming approach toward optimal design and planning of an integrated green biodiesel supply chain network under uncertainty: A case study", *Energy*, **156**, pp. 661-687 (2018). doi.org/10.1016/j.energy.2018.05.103
16. Babazadeh, R. "Application of fuzzy optimization to bioenergy supply chain planning under Epistemic Uncertainty: A new approach", Industrial & Engineering Chemistry Research, **58**, pp. 6519−6536 (2019). doi.org/10.1021/acs.iecr.8b05617
17. Babazadeh, R., Razmi, J., Pishvaee, M.S., et al. "A sustainable second-generation biodiesel supply chain network design problem under risk", *Omega*, **66**, pp. 258-277 (2017).

    doi.org/10.1016/j.omega.2015.12.010
18. Mousavi, A.P., Ghaderi, S.F., Azadeh, A., et al. "Hybrid multiobjective robust possibilistic programming approach to a sustainable bioethanol supply chain network design", *Industrial & Engineering Chemistry Research*, **57**, pp. 15066-15083 (2018). doi.org/10.1021/acs.iecr.8b02869
19. Mavrotas, G. "Effective implementation of the ε-constraint method in multi-objective Mathematical programming

problems", *Applied Mathematics and Computation*, **213**(2), pp. 455–465 (2009). doi.org/10.1016/j.amc.2009.03.037

20. Sahebjamnia, N., Torabi, S.A., and Mansouri, S.A. "Integrated business continuity and disaster recovery planning: Towards organizational resiliency", *European Journal of Operational Research*, **242**(1), pp. 261–273 (2015). doi.org/10.1016/j.ejor.2014.09.055

21. Ehrgott, M., *Multicriteria Optimization*, Springer, Berlin (2005). doi.org/10.1007/3-540-27659-9

22. Aghaei, J., Amjady, N., and Shayanfar, H.A. "Multi-objective electricity market clearing considering dynamic security by lexicographic optimization and augmented epsilon constraint method", *Applied Soft Computing*, **11**, pp. 3846–3858 (2011). doi.org/10.1016/j.asoc.2011.02.022

Biographies

Reza Babazadeh is an Associate Professor in the Faculty of Engineering at the University of Urmia, Urmia, Iran. He teaches undergraduate and graduate courses in industrial engineering, supply chain management, Engineering Economy, and Probability and Statics. He has published over 60 papers in peer-reviewed journals such Omega and Journal of Cleaner Production and con-ferences. His research interests include supply chain management, risk management, production planning under uncertainty, and forecasting.

Meisam Shamsi is a MSc graduate student in Industrial Engineering field from Urmia University, Urmia, Iran. He has published number of papers in peer-reviewed journals and conferences. His research interests include forecasting, ANN, optimization and supply chain management.