Green Design of Regional Wheat Supply Chains under Uncertainty

Reza Babazadeh*, Meisam Shamsi

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

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.

Keywords: Wheat Supply Chain, Optimization, Fuzzy Mathematical Programming, Uncertainty, Wheat Swap and Export

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, a 3.7 percent increase over the previous year [2]. Over the past 52 years, the country's wheat production shows

* Corresponding author. Tel.: +98 44 32972854; Fax: +98 44 32773591. E-mail addresses: r.babazadeh@urmia.ac.ir (R. Babazadeh); meisam.shamsi.93@gmail.com (M. Shamsi).
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 network optimization problem is reviewed. We have focused mainly on studies in the field of wheat supply chain optimization. Djuric and Götz [3] studied the combination of price transmission and gross margin analysis at the wheat-to-bread supply chain. 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 supply chain network that includes long-term supplier selection 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 supply chain 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 supply chain. 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 supply chain 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 supply chains. 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 supply chain. Sustainable collective innovation needs the participation of all partners in the wheat supply chain. Dossa et al. [11] used dimensions of transaction cost economics to investigate the effect of transactions in the circulation of circular economy in wheat supply chains in the 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 supply chains 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 supply chain network. Green development goals in supply chain (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 the next section, the proposed model for optimizing wheat supply chain 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 supply chain 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 supply chain 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 supply chain 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 supply chain 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 | Description |
|------|-------------|
| $F$  | 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 | Description |
|----------------------|-------------|
| $D_{kt}$            | 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 |
\[ \alpha_f \] Wheat harvest rate per hectare of rain-fed farms in province \( f \)
\[ \beta_f \] Wheat harvest rate per hectare of irrigated farms in province \( f \)
\[ SS_{st} \] Amount of wheat safety stock in province \( s \) in period \( t \)
\[ D_{fs} \] Distance between wheat farms in province \( f \) and silo in province \( s \) by transportation mode \( l \)
\[ D_{ss'} \] Distance between silo in province \( s \) and silo in province \( s' \) by transportation mode \( l \)
\[ D_{slk} \] Distance between silo in province \( s \) and domestic customer \( k \) by transportation mode \( l \)
\[ ECW_{ft} \] 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 \( t \)
\[ TCI_{fs} \] Transportation cost of wheat from province \( f \) to silo \( s \) by transportation mode \( l \) in period \( t \)
\[ TC2_{sl} \] Transshipment cost of wheat from silo \( s \) to silo \( s' \) by transportation mode \( l \) in period \( t \)
\[ TC3_{sk} \] Transshipment cost of wheat from silo \( s \) to domestic customer \( k \) by transportation mode \( l \) in period \( t \)
\[ PX_{sj} \] 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 \( f \)
\[ \omega_1 \] Environmental impact of adding one ton capacity for silos
\[ \omega_2 \] Environmental impact of storage per ton of wheat in silos
\[ \omega_3 \] Environmental impact of wheat shipment per ton from foreign suppliers
\[ \omega_4 \] Environmental impact of wheat transportation per ton per kilometer
\[ \omega_5 \] 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 \( t \)
\[ TW_{fs} \] Optimal amount of wheat transported from farms of province \( f \) to silos of province \( s \) by transportation model \( l \) in period \( t \)
\[ TD_{sl} \] Optimal amount of wheat transshipped from silos of province \( s \) to silos of province \( s' \) by transportation model \( l \) in period \( t \)
\[ TM_{sk} \] Optimal amount of wheat transported from silos of province \( s \) to domestic customer \( k \) by transportation model \( l \) in period \( t \)
\[ EX_{sj} \] 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:
\[ \text{Min } Z_1 = \sum_{f} \sum_{t} ECW_{ft} EWD_{ft} + \sum_{s} \sum_{t} ECA_{ft} EWA_{ft} + \sum_{s} \sum_{t} ECS_{st} ES_{st} \]
\[ + \sum_{f} \sum_{t} PCW_{ft} \alpha_f (FWD_f + EWD_{ft}) + \sum_{f} \sum_{t} PCA_{ft} \beta_f (FWA_f + EWA_{ft}) \]
\[ + \sum_{s} \sum_{t} HC_{st} HW_{st} + \sum_{s} \sum_{k} \sum_{t} KC_{ist} KW_{ist} \]
\[ + \sum_{s} \sum_{t} \sum_{k} \sum_{l} TC_{ist} TW_{flst} + \sum_{s} \sum_{k} \sum_{t} TC_{ist} TM_{slkt} \]
\[ + \sum_{s} \sum_{t} \sum_{k} \sum_{l} TC_{ist} TD_{slkt} - \sum_{s} \sum_{t} PX_{sjt} EX_{sjt} \]
\[ \sum_{s} \sum_{l} TM_{slkt} = D_{kt} \quad \forall k, t \] (3)
\[ \sum_{s} EX_{sjt} = DE_{jt} \quad \forall j, t \] (4)
\[ \sum_{s} TW_{flst} = \alpha_f (FWD_f + EWD_{ft}) + \beta_f (FWA_f + EWA_{ft}) \quad \forall f, t \] (5)
\[ HW_{st} = HW_{s,t-1} + \sum_{l} TW_{flst} + \sum_{s} \sum_{s} TD_{s'lst} - \sum_{s} \sum_{l} TD_{sls'} - \sum_{s} \sum_{l} TM_{slkt} \quad \forall s \in NIE, t \] (6)
\[ HW_{st} = HW_{s,t-1} + \sum_{f} \sum_{t} TW_{flst} + \sum_{s} \sum_{s} TD_{s'lst} + \sum_{s} KW_{ist} - \sum_{s} \sum_{l} TD_{sls'} \]
\[ - \sum_{s} \sum_{l} TM_{slkt} - \sum_{s} \sum_{l} EX_{sjt} \quad \forall s \in IE, t \] (7)
\[ HW_{st} \geq SS_{st} \quad \forall s, t \] (8)
\[ FWD_f + FWA_f + \sum_{t} EWD_{ft} + \sum_{t} EWA_{ft} \leq UW_f \quad \forall f \] (9)
\[ SES_{st} = SES_{s,t-1} + ES_{st} \quad \forall s, t \] (10)
\[ HW_{st} \leq FCS_{s} + SES_{st} \quad \forall s, t \] (11)
\[ FCS_{s} + SES_{st} \leq US_{st} \quad \forall s, t \] (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 supply chain and the environmental objective function minimizing the environmental impacts of the supply chain 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 supply chain network. These processes in the considered supply chain 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 supply chains [13]. This effect is intensified in wheat supply chains 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 supply chains. 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 $\varepsilon$-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 $\varepsilon$-constraint method is used to handle the multiple objectives of the proposed model.

- 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 supply chain 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].

\[
\begin{align*}
\text{Min} \quad & z = \bar{M}(\tilde{c}x) + \gamma \sigma(\tilde{c}x) \\
\text{s.t.} \quad & a_i x \geq b_i, \quad i = 1, \ldots, l \\
& a_i x = b_i, \quad i = l + 1, \ldots, m \\
& x \geq 0
\end{align*}
\]

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 \( \gamma \) (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:
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].

\[
\begin{align*}
\mu_c(x) = \begin{cases} 
0 & \text{if } x \in (-\infty, c^p] \\
1 & \text{if } x = c^m \\
g_c(x) = \frac{x - c^o}{c^o - c^m} & \text{if } x \in [c^m, c^o] \\
0 & \text{if } x \in [c^o, +\infty)
\end{cases}
\end{align*}
\]

(17)

\[
\begin{align*}
\text{Min } z = \left(\frac{c^p + 4c^m + c^o}{6}\right)x + \gamma \left(\frac{c^o - c^o}{3}\right)x,
\end{align*}
\]

s.t.

\[
\begin{align*}
&\left[(1-\alpha) \left(\frac{2}{3} a^m + \frac{1}{3} a^o\right) + \alpha \left(\frac{2}{3} a^m + \frac{1}{3} a^p\right)\right] x \\
\geq (1-\alpha) \left(\frac{2}{3} b^m + \frac{1}{3} b^p\right) + \alpha \left(\frac{2}{3} b^m + \frac{1}{3} b^o\right) & i = 1,\ldots,l
\end{align*}
\]

(18)

\[
\begin{align*}
&\left[\frac{1-\alpha}{2} \left(\frac{2}{3} a^m + \frac{1}{3} a^o\right) + \frac{\alpha}{2} \left(\frac{2}{3} a^m + \frac{1}{3} a^p\right)\right] x \\
\geq \left[\frac{\alpha}{2} \left(\frac{2}{3} b^m + \frac{1}{3} b^p\right) + \left(\frac{1-\alpha}{2}\right) \left(\frac{2}{3} b^m + \frac{1}{3} b^o\right)\right] x & i = l+1,\ldots,m
\end{align*}
\]

\[
\begin{align*}
&\left[1 - \frac{\alpha}{2} \left(\frac{2}{3} b^m + \frac{1}{3} b^p\right) + \frac{\alpha}{2} \left(\frac{2}{3} b^m + \frac{1}{3} b^o\right)\right] x \\
\leq \left[1 - \frac{\alpha}{2} \left(\frac{2}{3} b^m + \frac{1}{3} b^p\right) + \frac{\alpha}{2} \left(\frac{2}{3} b^m + \frac{1}{3} b^o\right)\right] x & i = l+1,\ldots,m
\end{align*}
\]

\[x \geq 0\]

- Handling multiple objective functions

The \(\varepsilon\)-constraint method is one of the most popular posteriori methods in which the Pareto-optimal set is achieved through changing the \(\varepsilon\)-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, \( f_i \)) subject to the feasibility constraints and constrained objectives and is stated as follows [20]:

\[
\min \{ f_i(x) \mid x \in X \land f_j(x) \leq \varepsilon_j, \quad i = 2, \ldots, p \}
\]  

(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 \( i \leq p \)

\[
f_i^{PIS} = \min \left\{ f_i(x) \mid x \in X \right\}
\]

\[
j = 1
\]

for \( j = 1 \) to \( p \) and \( j \neq i \)

\[
f_j(\hat{x}_{ji}) = \min \left\{ f_j(x) \mid x \in X \land f_i(x) \leq f_i^{PIS} + (1 - \alpha_1)(q_i f_i^{PIS}) \right\}
\]

\[
i = i + 1
\]

End While.

\[
f_i^{PIS} = f_i(x'_i), \quad i = 1, \ldots, p, \quad \text{where}
\]

\[
x'_i = \arg(\min \left\{ f_i(x) \mid x \in X \right\})
\]

\[
f_i^{NIS} = \min_{i=1,\ldots,p,i \neq j} \left\{ f_j(\hat{x}_{ji}) \right\}, \quad j = 1, \ldots, p, \quad \text{where}
\]

\[
\hat{x}_{ji} = \arg(\min \left\{ f_j(x) \mid x \in X \land f_i(x) \leq f_i^{PIS} + (1 - \alpha_1)(q_i f_i^{PIS}) \right\})
\]

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 the equation (20).
\[
\varepsilon_i = f_i^{NIS} - \left( \frac{f_i^{NIS} - f_i^{PIS}}{m} \right) \times n, \quad n = 0, 1, 2, ..., m
\]  

After calculating the \( \varepsilon \)-vectors, the augmented \( \varepsilon \)-constraint approach is applied as follows [22]:

\[
Min \{ f_i(x) - (r_i \times \sum_{i=2}^{n} s_i) \mid x \in X \land f_i(x) + s_i = \varepsilon_i \land s_i \in R^+, \quad i = 2, ..., p \}
\]  

Where \( r_i \) is the range of objective \( i \)th 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).

[Table 1, here]

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 2, here]

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 3, here]

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 4, here]

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.

[Table 5, here]

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.

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 $[0.8 \times D, 1.2 \times D]$. Foreign demand is changed in the range $[0.8 \times DE, 1.25 \times DE]$. All transportation costs are simultaneously changed in the range $[0.9 \times TC, 1.15 \times TC]$. 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.

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 supply chain 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.

![Figure 2, here](image2)
![Figure 3, here](image3)
![Figure 4, here](image4)

3.4. Policy Implications

The achieved results help the policy makers to make optimal decisions in wheat supply chains. 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 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 $\varepsilon$-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.

**5. 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).

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, 139–147 (2017).

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).

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*, doi: 10.24200/sci.2020.53772.3404 (2020).

7. Trisna, T., Marimin, M., Arkeman, Y. and Sunarti, T.C. “Fuzzy multi-objective optimization for wheat flour supply chain considering raw material substitution”, *International Journal of Industrial Engineering and Management*, 11(3), 180-191 (2021).

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), 685-705 (2020).

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).

10. Stanco, M., Nazzaro, C., Lerro, M. and Marotta, G. “Sustainable Collective Innovation in the Agri-Food Value Chain: The Case of the “Aureo” Wheat Supply Chain”, *Sustainability*, 12(14), 5642 (2020).

11. Dossa, A.A., Gough, A., Batista, L. and Mortimer, K. “Diffusion of circular economy practices in the UK wheat food supply chain”, *International Journal of Logistics Research and Applications*, 25(3), 328-347 (2022).

12. Deng, L., Zhang, H., Wang, C., Ma, W., Zhu, A., Zhang, F. and Jiao, X. “Improving the sustainability of the wheat supply chain through multi-stakeholder engagement”, *Journal of Cleaner Production*, 321, 128837 (2021).

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), 108-141 (2017).

14. Anderson E. and Monjardino M. “Contract design in agriculture supply chains with random yield”, *European Journal of Operational Research*, 277(3), 1072-1082 (2019).

15. Ghelichi Z., Saidi-Mehrabad M. and Pishvae M.S. (2018) “A stochastic programming approach toward optimal design and planning of an integrated green biodiesel supply chain network under uncertainty: A case study”, *Energy*, 156, 661-687.
16. Babazadeh R. “Application of Fuzzy Optimization to Bioenergy Supply Chain Planning under Epistemic Uncertainty: A New Approach”, *Industrial & Engineering Chemistry Research*, 58, 6519–6536 (2019).

17. Babazadeh R., Razmi J., Pishvaee M.S. and Rabbani M. “A sustainable second-generation biodiesel supply chain network design problem under risk”, *Omega*, 66, 258-277 (2017).

18. Mousavi A.P., Ghaderi S.F., Azadeh A. and Babazadeh R. “Hybrid Multiobjective Robust Possibilistic Programming Approach to a Sustainable Bioethanol Supply Chain Network Design”, *Industrial & Engineering Chemistry Research*, 57, 15066-15083 (2018).

19. Mavrotas G. “Effective implementation of the ε-constraint method in multi-objective Mathematical programming problems”, *Applied Mathematics and Computation*, 213(2), 455–465 (2009).

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), 261–273 (2015).

21. Ehrgott M. “Multicriteria optimization”, Springer, Berlin (2005).

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, 3846–3858 (2011).

**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 conferences. 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.

**Captions for the Figures and Tables:**

**Figure 1.** Wheat supply chain network

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

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

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

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

**Table 2.** Predicted demand of wheat for neighboring countries of Iran (t/y)
Table 3. Current capacity of silos, rain-fed and irrigated cultivation areas for each province
Table 4. Optimal amount of extension of rain-fed cultivation farms (ha)
Table 5. Optimal amount of capacity expansion of silos (t)
Table 6. Optimal amount of rain-fed wheat production in each period (t/y)
Table 7. Optimal amount of rain-fed wheat production in each period (t/y)
Table 8. Optimal amount of wheat storage in different provinces (t/y)
Table 9. Optimal export amount from different province to neighboring countries (t/y)
Figure 2. Changes of cost OF vs. domestic demand

Figure 3. Changes of cost OF vs. foreign demand


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

| Province        | Period | 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 | 225488 | 227086 | 228696 | 230318 | 231951 | 233595 | 235190 |
| Tehran          |        | 293075 | 296393 | 299730 | 301855 | 303995 | 306151 | 308321 | 310507 | 312708 | 314926 |
| 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.     |        | 121482 | 123248 | 125033 | 125919 | 126812 | 127711 | 128616 | 129528 | 130447 | 131371 |
| 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 |
| Khoristan       |        | 295656 | 299790 | 300536 | 301660 | 303798 | 305952 | 308122 | 310306 | 312506 | 314722 |
| Kerman          |        | 595774 | 604698 | 613622 | 617973 | 622354 | 626766 | 631210 | 635686 | 640193 | 644732 |

Figure 4. Changes of cost OF vs. transportation costs
| Province       | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|----------------|------|------|------|------|------|------|------|------|------|------|
| 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        | 346848 | 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)

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

| 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   | 0   | 739 |
| Kurdistan          | 166380 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| Kerman             | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
Table 5. Optimal amount of capacity expansion of silos (t)

| Province       | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 | Period 7 | Period 8 | Period 9 | Period 10 |
|----------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|
| Bushehr        | 84506    | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Khorasan J.    | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Zanjan         | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Hormozgan      | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0         |
| Markazi        | 60320    | 355      | 0        | 0        | 0        | 0        | 0        | 0        | 0        | 0         |

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

| Province       | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 | Period 6 | Period 7 | Period 8 | Period 9 | Period 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        | 395      | 395      | 395      | 395      | 395      | 395      | 395      | 395      | 395      | 395       |
| 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       |
| Province       | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 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| 5540| 5829| 5948| 6072| 2971| 246 | 246 |
| Gom            | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 25  | 3150|
| 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       | 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  |
| Province          | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 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)
| 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|
| Khorasan        | 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|

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