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# A mathematical programming model for sustainable agricultural supply chain network design under uncertainty

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*Abstract – Evaluating the sustainability in the crop supply chain plays an important role in creating an efficient supply chain and increasing food safety in developing countries. Therefore, in the present study, an efficient network of greenhouses, agricultural lands, processing plants, and agricultural distribution centers (farmer's markets) have been designed with regards to the sustainability dimension and with the purpose of minimizing the costs, minimizing the greenhouse gas emissions, and maximizing employment. The uncertainty has been identified as an inevitable part of studies in some parameters such as Brix, deterioration rate, employment rate, ideal yield, and water consumption rate. Also, the use of agricultural methods and techniques such as crop rotation policy, the use of nurtured seedling, and the consideration of Brix are among the issues that have been considered to increase the efficiency of the products and consequently to increase the economic efficiency. The model proposed with augmented ε-constraint method has been solved, and its efficiency has been investigated by presenting a case study in Iran. The results of the model solution indicate that the use of different planting policies, the consideration of Brix index, and effective attention to crop rotation policy has led to higher productivity of agricultural lands, production of higher quality products by expending lower prices and preserving environmental resources such as soil and water; so that the water consumption is reduced by 65.258%. Furthermore, the proposed model increases employment in the region and reduces unemployment by 11.2%*

***Keywords*** *– Brix, Crop Rotation, Deterioration, Sustainable Supply Chain, Fuzzy.*

## I. INTRODUCTION

The supply chain in the agricultural sector is complex and includes various manufacturing entities, all of which must respond to consumer demands in a sustainable and satisfactory manner (Derqui et al., 2016). The question that arises here is why it is important to discuss the supply chain in the agricultural sector in the literature review and policy-making. The answer to this question is rooted in the challenges of today's world at present. Due to the lack of income, poverty, and sustainability of food safety, many policymakers of Argo-industry development consider the effective improvement of crops supply chains as a strategy to solve existing problems. This strategy has a positive effect on employment in urban and rural areas, provides access to the market for farmers, and creates a connection between small

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and medium-sized businesses (Godfray et al., 2010; Donald, 2008). Hence, an efficient supply chain of crops can significantly reduce poverty and improve food safety in developing countries (Donald, 2008). Besides, in recent years, many researchers have decided to use the concept of sustainability in the design of supply chain networks of crops, while minimizing network costs and also the environmental and destructive effects of this industry. In the meantime, stakeholders of supply chains of crops are required to commit to fulfilling their social responsibilities in this field, which is usually created by governmental and non-governmental legislators or through the pressures of the global competitiveness. In other words, sustainable agriculture must be environmentally friendly, economically justifiable, and socially desirable at the same time (Allaoui et al.,2018; Castro & Swart, 2017; Kamble et al., 2020).

In the present paper, an efficient network of greenhouses, agricultural lands, food processing plants, and agricultural distribution centers (farmer’s markets) has been designed considering the concept of sustainable agricultural dimensions at different levels of the chain. The present research simultaneously takes into account the economic, environmental, and social dimensions by providing a multi-objective mathematical model with the objectives of reducing the costs, decreasing the greenhouse gas emissions, and increasing employment. According to the social dimension in the supply chain, agriculture is effectively planning for youth employment and decreasing the unemployment rate in developing areas. On the other hand, economic and environmental dimensions are also essential and require more efficient planning. It has been noted to the use of agricultural techniques such as cultivating crops from the same family, crop rotation policy, the use of nurtured seedling instead of direct use of seeds, the use of different irrigation methods to effectively preserve water resources and enrich the soil under cultivation, and approaching the ideal yield of agricultural fields and increasing the food safety. Harvesting the tomato with a better Brix increases the quality of the produced tomato paste, and it is necessary to focus on this parameter for the production of the tomato; it should be noted that it has been discussed in the present study by employing different planting policies. Degree Brix (°Brix) is known as an indicator of the amount of soluble solids concentration (SSC) in tomato fruits. The minimum reasonable limit for it is 20 and with increase the amount of Degree Brix in tomato, the quality of it and the concentration of the paste produced from it is increased (Le et al., 2018).

Many quantitative models in the field of sustainable supply chains have been developed under uncertainty conditions in parameters such as demand, warehouse capacity, shipping capacity, costs, etc. (Sazvar et al., 2014). In most real cases, complete information about some of the parameters is not available, and using fuzzy logic will increase the effectiveness and efficiency of the results and decisions. In the present study, due to the uncertain nature of some parameters, more effective modeling has been provided by using fuzzy logic in Brix index parameters, water consumption rate, crop deterioration rate, ideal agricultural yield, and employment rate.

In the following, other studies related to the subject, along with the research gaps in this field, will be mentioned. The problem description is presented in Section III and the problem is modeled and solved in Sections IV and V. A case study is reviewed in Section VI and also results analysis is presented in this section as numerical results and managerial insights. At the end the results of the research are summarized by providing the conclusion.

## II. LITERATURE REVIEW

Several important articles in the field of agricultural supply chains have been presented better to understand the history and necessity of this study. As discussed, researchers have been highly interested in the sustainability of supply chains in the agricultural sector in recent years. In this field, Van et al. (2009) evaluate the food supply chains by increasing consumer demand in terms of quality and sustainability. In this study, a new integrated approach has also been proposed about logistics, sustainability, and the analysis of food quality. In a study conducted by Blackburn & Scudder (2009), the strategies for supply chain design have been employed for a specific type of deteriorable product, such as melons and corn. They calculated the rate that the product loses over time in the supply chain using the product's time margin. Quadra et al. (2009) developed a multi-functional, multi-location, and multi-product sustainable supply chain model with the purpose of minimizing the total cost of the system using the resource level of production and distribution. Catalá et al. (2013) presented a strategic planning model for the optimal reconstruction of a pomegranate production farm about various planting densities. The model decides with what type of optimal investment policy for a given farm to maximize the net present value of the business. Govindan et al. (2014) reviewed a sustainable supply chain and proposed a multi-objective optimization model by integrating sustainability in decision making and distribution in the food supply chain network. Rocco et al. (2016a) have presented a linear planning model for production and logistics planning with the processing industry of Brazilian tomato, which adequately supports the decision-making in agricultural and industrial activities. Rocco et al. (2016b) claim that the number of dissolved solid content in tomato, known as "Brix" and the efficiency of the product are the most important uncertain parameters for determining technical and economic performance in the tomato processing industry; hence they have performed a research on this area. Ghezavati et al. (2017) presented a mathematical model of complex mixed-integer programming in a periodic manner for the distribution of fresh agricultural food, since the proposed model is solved using the Bender's decomposition method. Silva et al. (2017) proposed an integrated approach for making decisions about purchasing, transportation and storage of fresh productions. Li et al. (2019) have proposed an optimization model for resource allocation to the sustainable management of agricultural water, food, and energy. Ren et al. (2019) claimed that the optimal allocation of water and agricultural land is a complex system that includes multiple objectives. Also, uncertainty about the optimal allocation of water and irrigation land is inevitable. For this purpose, they have developed an improved multi-purpose random fuzzy planning. The developed model deals with a case study in China. The maximum net profit, the maximum efficiency of agricultural water, and the minimum irrigation area have been considered as planning objectives in this research. Banasik et al. (2019) addressed the supply chain of food products and evaluated the mushrooms' production plan. In this study, a possibilistic two-levels model has been presented by addressing the economic and environmental aspects. Mogale et al. (2019) evaluated the distribution system of the food supply chain concerning sustainability and thus proposed a two-objective model with the aim of reducing environmental costs and environmental pollutants. Moghadam et al. (2019) presented a mathematical model for a sustainable production system of deteriorable products in the reverse supply chain. In this research, the objective of the satisfaction level of using technology has been proposed as a social dimension. Sinha & Anand (2020) have conducted a study on the optimization of the supply chain of deteriorable products by addressing environmental considerations. Temporary warehouses have been employed according to the concept of deteriorable products. Krishnan al. (2020) presented the redesign of the supply chain to provide food products in a sustainable environment. In this study, a conceptual model with regards to the environmental, ecological, and economic dimensions has been evaluated.

A summary of the contents, as mentioned above, is presented in Table I. In this table, the different dimensions of previous studies in terms of decision levels and variables, the sustainability of the studied chain, and the used solution methods are compared. The main purpose of this table is to indicate the research gaps in the subject of this field and also providing the similarities and differences between the studies of other researchers with the main subject of the present research.

According to the literature review, a small number of articles have evaluated all three dimensions of sustainability, and inadequate attention has been paid to the social dimension. Since one of the most important issues in governmental macro planning is the planning for youth employment and reducing the unemployment rate in developing regions, the establishment of factories and also industrial and agricultural centers in areas with higher unemployment rates leads to the recruitment of workforce and the growth of less developed regions in the country. Hence, the high volume of migration to large and densely populated cities will be reduced, and the sharing of facilities in different regions of the country will increase. The establishment of industrial and agricultural centers in the form of the development of processing plants in regions leading to higher employment is one of the subjects of the current paper, which has been considered in line with social responsibilities.

**TABLE I. Summary of papers reviewed in agricultural supply chains**

| Considerations | | Quality | Quality | Crop Rotation | - | - | Brix Degree | Brix Degree | Quality | - |
|---|---|---|---|---|---|---|---|---|---|---|
| Solution Method (Tool) | | Simulation | Exact (GAMS) | Exact (Branch & Bound) | Exact (GAMS) | Hybrid Meta-heuristic | Exact (GAMS) | Exact (GAMS) | Exact (Benders Decomposition) | Exact (εConstraint) |
| Uncertainty component | | Logistic, Quality | - | - | - | - | - | Yield, Brix | - | - |
| The type of objective function | Economical | Cost | Cost | Cost | Profit | Cost | Cost | Cost | Profit | Cost |
| | Social | - | - | - | - | - | - | - | - | - |
| | Environmental | Energy use, environmental effects | - | Optimal use of resource, organic fertilizers | - | greenhouse gas emissions | - | - | - | - |
| Outputs | Cultivation | - | - | ✓ | ✓ | - | - | - | - | - |
| | Harvesting | - | - | ✓ | - | - | ✓ | ✓ | - | - |
| | Production | - | ✓ | - | ✓ | - | ✓ | ✓ | - | - |
| | Distribution | ✓ | ✓ | - | - | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Inventory | ✓ | - | ✓ | - | - | - | - | ✓ | ✓ |
| Decision-making Level | Strategic | ✓ | - | - | ✓ | ✓ | - | - | ✓ | - |
| | Tactical | ✓ | ✓ | ✓ | - | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Operative | ✓ | - | ✓ | - | - | - | - | - | - |
| Reviewed Papers | | Van et al. (2009) | Blackburn & Scudder (2009) | Quadra et al. (2009) | Catalá et al. (2013) | Govindan et al. (2014) | Rocco & Morabito (2016a) | Rocco & Morabito (2016b) | Ghezavati et al. (2017) | Silva et al. (2017) |

**Continue TABLE I. Summary of papers reviewed in agricultural supply chains**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Considerations | | - | - | - | - | - | - | - | Brix Degree, Crop rotation, Ecesis Cultivation Policy |
| Solution Method (Tool) | | Heuristic | AHP, Minimum deviation method | Simulation | Meta-heuristic (MOPSO and NSGA-II) | Exact (GAMS) | Meta-heuristic (IBFA) | Life Cycle Assessment | Exact (Augmented ε-Constraint) |
| Uncertainty component | | Energy, food and water sources | The share of crop irrigation | Demand, Yield | - | - | - | - | Brix Degree, Deterioration Rate, Employment Rate, Water Consumption, Performance Index |
| The type of objective function | Economical | Profit | Profit | Profit | Cost | Profit | Cost | Cost | Cost |
| | Social | - | - | - | - | Satisfaction with Technology | - | - | Creating Job Opportunities in the Region |
| | Environmental | Water Quality, $CO_2$ Emission | Water Quality, Reduce irrigation areas | Environmental Effects | $CO_2$ Emission | Environmental Effects | - | Resources Consumption | $CO_2$ Emission, Water Consumption |
| Outputs | Cultivation | ✓ | ✓ | ✓ | - | - | - | - | ✓ |
| | Harvesting | ✓ | ✓ | ✓ | - | - | - | - | ✓ |
| | Production | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| | Distribution | - | - | - | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Inventory | - | - | - | ✓ | - | - | - | - |
| Decision-making Level | Strategic | - | - | - | ✓ | - | - | ✓ | ✓ |
| | Tactical | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Operative | - | - | ✓ | - | - | ✓ | - | - |
| Reviewed Papers | | Li et al. (2019) | Ren et al. (2019) | Banasik et al. (2019) | Mogale et al. (2019) | Moghaddam et al. (2019) | Sinha & Anand (2020) | Krishnan al. (2020) | Current Study |

As can be seen in Table I, many researchers have made the emission of pollutants and greenhouse gases to be a part of their research because of its importance in the agricultural industry. Although a small number of studies have been conducted on other aspects of environmental protection. Preserving water resources and preventing the erosion of agricultural lands because of lack of attention to proper planning will lead to the destruction of a significant part of environmental resources. Thus, in the present study, in addition to considering the emission of pollutants and greenhouse gases, the use of agricultural methods and techniques such as the use of greenhouses for the growth and cultivation of seedling instead of direct use of plant seeds, the use of yield factor and water requirements of the products, and also the use of appropriate irrigation methods to reduce water consumption have been considered. The use of nurtured seedling in greenhouses for planting the crops due to the high production capacity per hectare, the use of indoor space and shortening the harvest period, has led to a less water demand and is capable of reducing the water consumption by $\frac{1}{8}$ compared the planting the crops with seeds. On the other hand, considering crop rotation in the cultivating crops from the same family is one of the issues that have been considered in order to enrich agricultural soil and preserve environmental resources. The crop rotation means the continuous cultivation of different plants for one or more years based on a particular order in a fixed land. Although farmers have experimentally observed the effects of crop rotation on increasing the productivity of crops, crop rotation is a completely specialized issue, so that the nutritional needs, ecological and physiological conditions, and other issues related to the plant should be considered. The continuous cultivation of a crop is not only economically affordable, but also gradually leads to erosion of agricultural land. Hence, in the present study, four crops from the same family have been frequently considered for cultivating in agricultural lands for the purpose of increasing the productivity of the agricultural lands. The purpose of defining this type of problem is to use the crop rotation policy to increase the productivity of crops and, consequently, raise the economic returns.

Finally, it should be noted that the Brix index or percentage of dissolved solid content in a solution is one of the important indexes in the preparation of some food products such as tomato paste and there was a small number of studies on its importance in optimization and design of the supply chain network of food products. Considering the Brix index leads to the achievement of higher quality products and an increase in food safety by spending fewer resources on financial and environmental capital. Therefore, in the current study, the Brix index is considered as a part of modeling to divide products between processing plants and consumer markets.

In addition, considering the uncertainty in the studies will make the problem to be practical for decision-makers and executors and also to be closer to the real world. Thus, some important factors such as the unemployment rate, the amount of water consumed by crops, the deterioration rate, the Brix of tomatoes, and the ideal yield factor of agricultural lands have been considered to be fuzzy due to their uncertainty nature. The uncertainty in these parameters has been uniquely considered in the present study.

Finally, the innovations and distinctions of the present research can be compared to the previous studies as follows:

- The design of a multi-product, multi-period, and multi-level supply chain network for crops.
- Simultaneously considering the sustainability dimensions in the economic (reducing costs), in the environmental (reducing greenhouse gas emissions, decreasing water consumption, and soil conservation), and in the social (focusing the unemployment using the recruitment in the third level of the studied chain).
- Considering the different cultivation policies to preserve environmental resources, increase the productivity of cultivated lands, and make better decisions in reducing costs.
- The use of fuzzy logic in the parameters of the employment rate, water consumption of products, deterioration rate, Brix, and ideal yield factor.
- The focus is on producing tomato products with the desired Brix, followed by increasing the quality of the processed product and maintaining food safety.

## III. PROBLEM DESCRIPTION

In the present study, there are forward, centralized and three-level supply chains, in which the greenhouses, agricultural lands, and candidate factories and farmer's markets are placed in the first, second, and third levels, respectively. The studied four products were selected from four products from Solanaceae (tomato, eggplant, bell pepper, and potato) due to the similar cultivation conditions and harvest time and production capability in Iran. According to the statistics of the Ministry of Agriculture, the products of Solanaceae are cultivated in water, and the share of the amount of dry farming of these products is significantly minor. Moreover, three greenhouses have been used to produce and nurture seedling products. Due to the limited capacity of greenhouses, it is not possible to meet the total demand of downstream agricultural lands by nurturing seedlings; hence, the use of seedling is selected as one of the planting methods in each period. Simultaneously with the use of the method of crop cultivation using the nurtured seedling, three other methods can be employed for cultivating the crops. These three methods include the combination of three irrigation methods with the different types of seeds in each period. The presentation of all four methods is in line with the increase in the productivity of agricultural land and the amount of Brix in tomato products.

On the other hand, farmers plant crops without any plans and in accordance with the price fluctuations, while continuous and sequential cultivation of a product is not only economically affordable but also gradually leads to the erosion of agricultural land. Therefore, in order to increase the productivity of the land, the cultivation of four crops from the same family in agricultural fields has been considered to be continuous. Furthermore, the use of crop rotation policy increases the productivity of crops and consequently raises the economic returns.

In the third level of the chain, there are processing plants that only produce one type of product; hence, they have been considered as candidate centers for the development of production lines for canned food, food products, and spices. Starting up the candidate factories can increase the employment rate in the studied region due to the costs of developing the production lines.

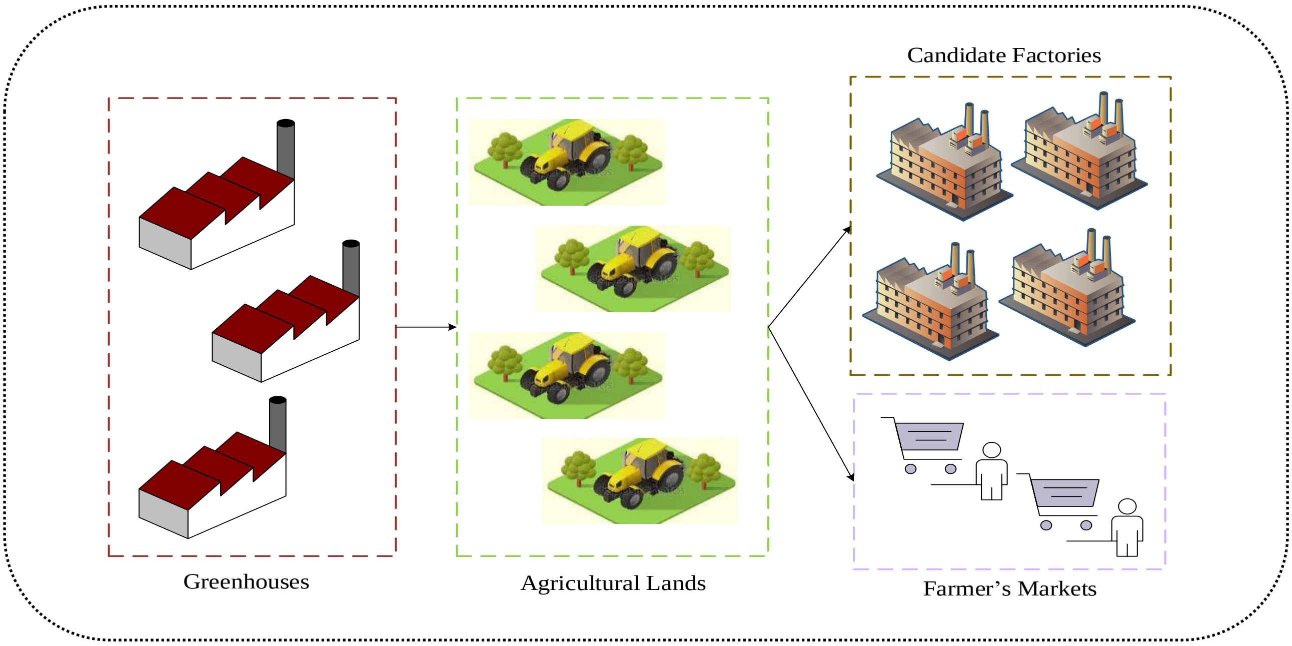


**Fig. 1. The crops supply chain of this study**

In the present study, the authors intend to achieve an ideal plan for the entire chain by considering the costs, the emission levels of greenhouse gases, and the employment rate in the region. Therefore, the objective functions of the study include minimizing the costs, minimizing the emissions of greenhouse gasses, and maximizing employment. In this regard, the proposed model determines what products to be cultivated at what time, to what extent, with what cultivation policy and on what farm, and also how much of the harvested products to be delivered to developed factories in each period and how much to be sent to farmer's markets. The studied supply chain is indicated in Fig (1).

*Assumptions:*

- Considering a centralized three-level supply chains, containing the greenhouses, agricultural lands, and candidate factories and farmer's markets.

- Considering tomatoes, potatoes, eggplant, and bell peppers as the studied products
- Considering the multiple periods.
- The amount of harvest from each crop in every period is the same as the amount cultivated at the beginning of the period.
- Cultivation of crops is performed in water with regards to the limitations of water resources.
- Considering the different methods of cultivating the crops, i.e., using different combinations of seed types with different irrigation methods or using seedling, which is different in cost and quality and also water consumption.
- Considering the level of emission of greenhouse gases from the shipping of products, cultivation and nurturing the seedling.
- Providing an ideal yield for all four products and the Brix index for tomatoes (the Brix is referred as the percentage of dissolved solid content in a solution, and the ideal yield implies to the amount of product harvested per hectare of agricultural land).
- Considering the crop rotation policy.
- Considering the different employment rates for the development of processing plants.
- Considering the deterioration rate of products during the shipping route.
- The cost of shipping and the level of emission of pollutants from the cultivation and shipping of products depend on their weight.
- Considering the uncertainty in the parameters including employment rate, water consumption rate, deterioration rate, Brix of tomatoes, and ideal yield. The rest of the parameters are assumed to be fixed and determined.
- The capacity of greenhouses, agricultural land and processing plants is limited.
- In processing plants and farmer's markets, no return can be made.
- There is ability to replant the crop on agricultural land after harvesting the products.
- Transportation costs vary at different levels of the supply chain.
- Products are crops (not horticultural crops).

## IV. MODELING

In this section, the sets, parameters, and variables of the problem will be presented, and then the modeling of the problem will be discussed.

### A. Notations

*Sets:*

$i \in I$ Set of products

$j \in J$ Set of greenhouses

$f \in F$ Set of agricultural lands

$m \in M$ Set of candidate factories

$n \in N$ Set of farmer's markets

$k \in K$ Set of cultivation methods

$t \in T$ Set of periods

*Parameters:*

| | |
|---|---|
| $C_{ijt}$ | Cost of nurturing *i*th seedling of product in *j*th greenhouse and *t*th period (Rials per ton) |
| $C'_{ijft}$ | The shipping cost of *i*th product from *j*th greenhouse to *f*th land in *t*th period (Rials per ton) |
| $A_{ikft}$ | Cost of cultivating and harvesting *i*th product by *k*th method in *f*th land and *t*th period (Rials per ton) |
| $A'_{ikfmt}$ | Cost of delivering the *i*th product to the *m*th factory in the *t*th period, which was cultivated by the *k*th method in *f*th land (Rials per ton) |
| $B_{ifnt}$ | The shipping cost of *i*th product from *f*th land to *n*th farmer market in *t*th period (Rials per ton) |
| $M_m$ | Cost of building the *m*th factory (Rials) |
| $Cap_j$ | The capacity of *j*th greenhouse (ton) |
| $\tilde{W}_{ikft}$ | Amount of water consumed by the *i*th product, which was cultivated by the *k*th method in *f*th land and *t*th period ($m^3$ per hectare) |
| $R$ | Annual precipitation ($m^3$) |
| $\tilde{\theta}_{im}$ | Deterioration rate of *i*th product during the process of delivering to *m*th factory (%) |
| $\tilde{\theta}_{in}$ | Deterioration rate of *i*th product during the process of delivering to *n*th farmer market (%) |
| $D_{imt}$ | The demand of *m*th factory for *i*th product in *t*th period (ton) |
| $D'_{int}$ | The demand of *n*th farmer market for *i*th product in *t*th period (ton) |
| $O^{\min}$ | Minimum employment required (%) |
| $\tilde{O}_m$ | Employment percentage of *m*th factory (%) |

| | |
|---|---|
| $\tilde{\alpha}_{ikf}$ | Ideal yield of *i*th product which was cultivated by *k*th method in *f*th land (ton per hectare) |
| $F_f$ | The capacity of *f*th land (hectare) |
| $\tilde{B}r_{ikf}$ | Brix of *i*th product, which was cultivated by *k*th method in *f*th land |
| $Br^{\min}$ | Minimum Brix required to produce the processed products |
| $Ga$ | Conversion coefficient of gasoline to carbon |
| $L_{ijft}$ | Amount of gasoline used for the shipping the amount of *i*th product to be delivered from the *j*th greenhouse to the *f*th land in the *t*th period (gram per ton) |
| $L'_{ikfmt}$ | Amount of gasoline used for shipping the amount of *i*th product to be delivered to *m*th factory in *t*th period, which was cultivated by the *k*th method in *f*th land (gram per ton) |
| $L''_{ifnt}$ | Amount of gasoline used for shipping the amount of *i*th product to be delivered from the *f*th land to the *n*th farmer market in *t*th period (gram per ton) |
| $GHG_{ijt}$ | Rate of carbon emissions from the production of seedling of *i*th product in the *j*th greenhouse during the *t*th period (gram per ton) |
| $Q_m$ | Rate of carbon emissions from the construction of *m*th factory (gram) |
| $M$ | A considerably large positive number |

*Decision Variables:*

| | |
|---|---|
| $X_{ijt}$ | Amount of nurtured seedling from *i*th product in *j*th greenhouse and *t*th period (ton) |
| $Z_{ijft}$ | Amount of *i*th product which is delivered from the *j*th greenhouse to the *f*th land in *t*th period (ton) |
| $V_{ikft}$ | Amount of crop cultivated/harvested from the *i*th product by the *k*th method in the *f*th land and *t*th period (ton) |
| $E_{ifnt}$ | Amount of *i*th product which is delivered from the *f*th land to the *n*th farmer market in *t*th period (ton) |
| $G_{ikfmt}$ | Amount of *i*th product cultivated by the *k*th method in the *f*th land and is delivered to *m*th factory in *t*th period (ton) |
| $Y_{ijt}$ | If the seedling of *i*th product is nurtured in *j*th greenhouse and *t*th period, it will be equal to 1, otherwise will equal 0 |

| | |
|---|---|
| $ZZ_{ikft}$ | If the *i*th product is cultivated by *k*th method in *f*th land and *t*th period, it will be equal to 1, otherwise will equal 0 |
| $P_m$ | If *m*th factory is developed, it will be equal to 1, otherwise will equal 0 |

### *B. Proposed Mathematical Model*

According to the described assumptions and symbols, the proposed mathematical model is as follows:

$$Min\ Z_1 = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T} X_{ijt} C_{ijt} Y_{ijt} + \sum_{i\in I}\sum_{j\in J}\sum_{f\in F}\sum_{t\in T} C'_{ijft} Z_{ijft} + \sum_{i\in I}\sum_{k\in K}\sum_{f\in F}\sum_{t\in T} A_{ikft} V_{ikft} ZZ_{ikft}$$
$$+\sum_{i\in I}\sum_{k\in K}\sum_{f\in F}\sum_{m\in M}\sum_{t\in T} A'_{ikfmt} G_{ikfmt} + \sum_{i\in I}\sum_{f\in F}\sum_{n\in N}\sum_{t\in T} B_{ifnt} E_{ifnt} + \sum_{m\in M} M_m P_m \tag{1}$$

$$Min\ Z_2 = Ga\left(\sum_{i\in I}\sum_{j\in J}\sum_{f\in F}\sum_{t\in T} L_{ijft} Z_{ijft} + \sum_{i\in I}\sum_{k\in K}\sum_{f\in F}\sum_{m\in M}\sum_{t\in T} L'_{ikfmt} G_{ikfmt} + \sum_{i\in I}\sum_{f\in F}\sum_{n\in N}\sum_{t\in T} L''_{ifnt} E_{ifnt}\right)$$
$$+\sum_{i\in I}\sum_{j\in J}\sum_{t\in T} GHG_{ijt} X_{ijt} + \sum_{m\in M} Q_m P_m \tag{2}$$

$$Max\ Z_3 = \sum_{m\in M} \tilde{O}_m P_m \tag{3}$$

*S.T.*

$$\sum_{i\in I} X_{ijt} \le Cap_j \qquad \forall j \in J, t \in T \tag{4}$$

$$\sum_{j\in J} Z_{ijft} = V_{i1ft} \qquad \forall i \in I, f \in F, t \in T \tag{5}$$

$$X_{ijt} = \sum_{f\in F} Z_{ijft} \qquad \forall i \in I, j \in J, t \in T \tag{6}$$

$$\sum_{f\in F}\sum_{n\in N} E_{ifnt} + \sum_{k\in K}\sum_{f\in F}\sum_{m\in M} G_{ikfmt} = \sum_{f\in F}\sum_{k\in K} V_{ikft} \qquad \forall i \in I, t \in T \tag{7}$$

$$\sum_{k\in K}\sum_{f\in F} G_{ikfmt}(1-\tilde{\theta}_{im}) \ge D_{imt} \qquad \forall i \in I, m \in M, t \in T \tag{8}$$

$$\sum_{f \in F} E_{ifnt}(1-\tilde{\theta}_{in}) \geq D'_{int} \qquad \forall i \in I, n \in N, t \in T \tag{9}$$

$$\sum_{k \in K} ZZ_{ikft} + ZZ_{ikft+1} \leq 1 \qquad \forall i \in I, f \in F, t \in T \tag{10}$$

$$0 < \sum_{\substack{k \in K \\ k \neq 1}} ZZ_{ikft} + ZZ_{i1ft} \leq 2 \qquad \forall i \in I, f \in F, t \in T \tag{11}$$

$$\sum_{\substack{k \in K \\ k \neq 1}} ZZ_{ikft} \leq 1 \qquad \forall i \in I, f \in F, t \in T \tag{12}$$

$$\sum_{i \in I} \sum_{k \in K} \sum_{f \in F} \sum_{t \in T} G_{ikfmt} \leq M \times P_m \qquad \forall m \in M \tag{13}$$

$$Z_{ijft} \leq M \times Y_{ijt} \qquad \forall i \in I, j \in J, f \in F, t \in T \tag{14}$$

$$E_{ifnt} \leq M \times ZZ_{ikft} \qquad \forall i \in I, k \in K, f \in F, n \in N, t \in T \tag{15}$$

$$G_{ikfmt} \leq M \times ZZ_{ikft} \qquad \forall i \in I, j \in J, k \in K, f \in F, m \in M, t \in T \tag{16}$$

$$V_{ikft} \leq M \times ZZ_{ikft} \qquad \forall i \in I, k \in K, f \in F, t \in T \tag{17}$$

$$\sum_{m \in M} \tilde{O}_m P_m \geq O^{\min} \tag{18}$$

$$\sum_{k \in K} \sum_{f \in F} \tilde{B}r_{1kf} G_{1kfmt} \geq Br^{\min} D_{1mt} \qquad \forall m \in M, t \in T \tag{19}$$

$$\sum_{i \in I} \sum_{k \in K} \sum_{f \in F} \sum_{t \in T} \tilde{W}_{ikft} ZZ_{ikft} \leq R \tag{20}$$

$$\sum_{k \in K} V_{ikft} / \tilde{\alpha}_{ikf} \leq F_f \qquad \forall i \in I, f \in F, t \in T \tag{21}$$

$$X_{ijt}, Z_{ijft}, V_{ikft}, E_{ifnt}, G_{ikfmt} \geq 0 \qquad \forall i \in I, j \in J, k \in K, f \in F, m \in M, n \in N, t \in T \tag{22}$$

$$Y_{ijt}, ZZ_{ikft}, P_m \in \{0,1\} \qquad \forall i \in I, j \in J, k \in K, f \in F, m \in M, t \in T \tag{23}$$

The objective function (1) minimizes the cultivation cost of seedling in greenhouses, the cost of cultivating/harvesting products from agricultural lands, the cost of transferring to agricultural lands and processing plants and farmer's markets, and the cost of setting up new lines in candidate factories. The objective function (2) refers to the minimization of the emission of greenhouse gases resulted from the transfer of seedling and products, greenhouses, and the starting up of lines in factories. The conversion coefficient of gasoline to carbon has been considered to convert the level of emission of pollutants caused by shipping the products. The objective function (3) increases employment by considering the employment rate. Constraint (4) refers to the limitation of the capacity greenhouses. Constraint (5) shows that the first production method is the seedling cultivation policy and balances the cultivation rate of crops through the first method. Constraints (6) and (7) respectively imply balancing the rate of shipping from greenhouses to agricultural lands and the rate of shipping from agricultural lands to factories and farmer's markets. Constraints (8) and (9) respectively meet the demand of factories and farmer's markets. Constraint (10) guarantees that only one crop will be cultivated on each land in each period; the crop rotation is actually expressed. Constraints (11) and (12) guarantee that only one of the cultivation methods will be used for the products. Constraint (13) guarantees that products will be delivered to the factory when new production lines are established in the factory. Constraints (14), (15), (16) and (17) respectively guarantees that the products will be delivered to agricultural lands in the case of cultivating the seedling in a greenhouse, and the products will be delivered to the factories and farmer's markets in the case of cultivating and harvesting the productions in lands in that period. These constraints are provided to reduce the number of problem variables and ensure the problem conditions. Constraint (18) will meet the minimum employment rate in factories. Constraint (19) guarantees the estimated minimum Brix for the production of tomato paste. This constraint has only been defined for the tomato crop. Constraint (20) refers to the calculation of the maximum amount of water used in agricultural lands in each period, which should be less than the amount of precipitation in that period. Constraint (21) ensures that the rate of cultivating/ harvesting in each land, and every period does not exceed the capacity of the land. Finally, constraints (22) and (23) also demonstrate the limitations related to problem decision variables.

## V. SOLUTION METHOD

This section consists of three sub-sections as follows:

### *A. Linearization*

The proposed model is a nonlinear mixed-integer programming model. Before solving the model, in order to improve the ideal solution, we make the model linear and therefore more tractable by using some theoretical techniques. In current study the bilinear terms such as $X_{ijt}Y_{ijt}$ and $V_{ikft}ZZ_{ikft}$ make the proposed model nonlinear. Without loss of generality, suppose that variable $x$ is a positive variable and variable $y$ is a binary variable, so a bilinear term is presented as x.y, which can be replaced by introducing a new positive auxiliary variable z. Therefore, by introducing a new variable and adding the following constraints, it can be altered to an equivalent linear model as follows:

$x.y \rightarrow z$

$x - (1 - y) \times M \leq z \leq x$

$z \leq M \times y$

Also, M is an arbitrary large number.

The proposed model is nonlinear due to the multiplication of the binary variable in the positive variable that has been used in the objective function (1), the following equations are used for linearization according to paper of Glover, (1975).

$$X_{ijt}Y_{ijt} = U_{ijt} \qquad \forall i \in I, j \in J, t \in T \tag{24}$$

$$V_{ikft}ZZ_{ikft} = R_{ikft} \qquad \forall i \in I, k \in K, f \in F, t \in T \tag{25}$$

Now the following constraints will be added to the equations:

$$U_{ijt} \leq X_{ijt} \qquad \forall i \in I, j \in J, t \in T \tag{26}$$

$$U_{ijt} \leq M * Y_{ijt} \qquad \forall i \in I, j \in J, t \in T \tag{27}$$

$$U_{ijt} \geq X_{ijt} + \mathrm{M}*(\mathrm{Y}_{ijt} - 1) \qquad \forall i \in I, j \in J, t \in T \tag{28}$$

$$R_{ikft} \leq V_{ikft} \qquad \forall i \in I, k \in K, \in F, t \in T \tag{29}$$

$$R_{ikft} \leq M * ZZ_{ikft} \qquad \forall i \in I, k \in K, \in F, t \in T \tag{30}$$

$$R_{ikft} \geq V_{ikft} + \mathrm{M}*(\mathrm{ZZ}_{ikft} - 1) \qquad \forall i \in I, k \in K, \in F, t \in T \tag{31}$$

Now, the nonlinear equation converts to the following form by the linearization of variables:

$$\begin{aligned} Min\ Z_1 = &\sum_{i \in I}\sum_{j \in J}\sum_{t \in T} C_{ijt}U_{ijt} + \sum_{i \in I}\sum_{j \in J}\sum_{f \in F}\sum_{t \in T} C'_{ijft}Z_{ijft} + \sum_{i \in I}\sum_{k \in K}\sum_{f \in F}\sum_{t \in T} A_{ikft}R_{ikft} \\ &+ \sum_{i \in I}\sum_{k \in K}\sum_{f \in F}\sum_{m \in M}\sum_{t \in T} A'_{ikfmt}G_{ikfmt} + \sum_{i \in I}\sum_{f \in F}\sum_{n \in N}\sum_{t \in T} B_{ifnt}E_{ifnt} + \sum_{m \in M} M_m P_m \end{aligned} \tag{32}$$

### *B. Possibilistic Programming Method*

Possibilistic programming models are presented for solving linear programming problems with inaccurate parameters. In this type of problem, the basic assumption is that the input data of the problem has been prepared based on the available information from the past and the opinions of experts and has been modeled by the distribution of possibilities. Among the methods of possibilistic programming, the method presented by Jiménez et al. (2007) is one of the most efficient methods that use strong and valuable concepts in the process of defuzzification of the basic modeling. In this method, first, the uncertain objective functions are converted to a definite mode using the expected value range of the related parameters, and after determining the minimum acceptable degree to provide possibilistic limitations ( $\beta$ ) by the decision-maker, the possibilistic limitations are converted to a definite mode. In order to better explain this method, first, the membership function of fuzzy numbers is defined and then the method of calculating the expected value of a fuzzy number is presented. Finally, the details of the process of defuzzification of a possible model are stated. The fuzzy logic first introduced by Zadeh (1965) extends the notion that an element can be partially but not entirely a member of a set. In fact, in fuzzy sets, the membership rate is relative. A fuzzy set is defined by a membership function whose curve is more in line with human thinking and behavior. While in a classic set. If the degree of membership of an element of a set is equal to zero, it means that that member does not exist in the set, and if the degree of membership of a member is equal to one, it means that that member is completely in the set. But if the membership degree of a member is between zero and one, this number indicates the gradual membership. Common membership functions are triangular, trapezoidal, gaussian, and bell membership functions. The following figure shows an example of the membership function of Triangular Number $\tilde{A}$. In this possibility distribution, the values $a_1$, $a_2$ and $a_3$ present the most pessimistic, possible and optimistic values of each parameter, respectively.

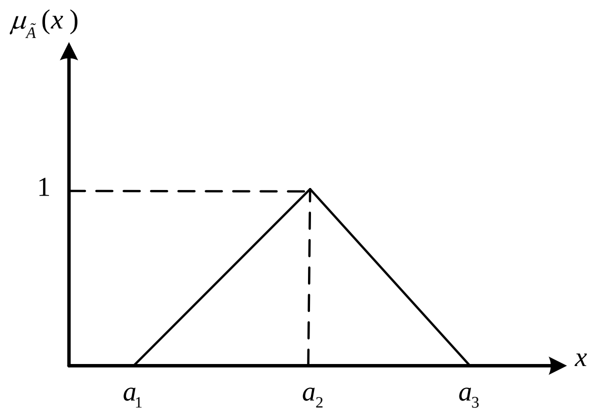


**Fig. 2. Membership function of Triangular Number**

In Jiménez et al. (2007) method, fuzzy numbers can have any kind of possibility distribution function, which is one of the advantages of this method over other methods. Assume that the fuzzy number membership function is defined as follows.

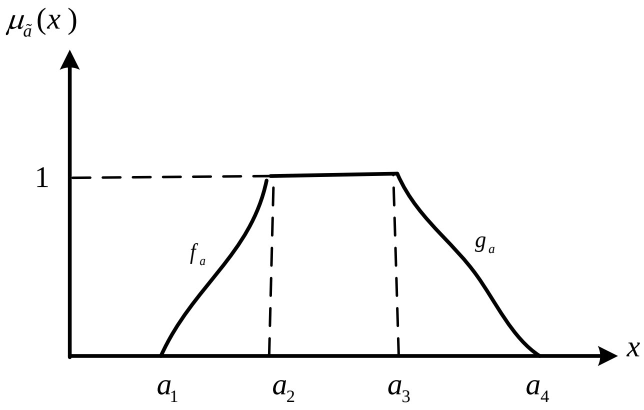


**Fig. 3. Membership function of fuzzy number**

$$\begin{cases} 0 & \forall x \in (-\infty, a_1] \cup [a_4, +\infty) \\ f_a(x) & \forall x \in [a_1, a_2] \\ 1 & \forall x \in [a_2, a_3] \\ g_a(x) & \forall x \in [a_3, a_4] \end{cases} \tag{33}$$

Where $f_a(x)$ is an ascending function and $g_a(x)$ is a descending function. As shown in Fig (3), if these functions are linear, the fuzzy number $\tilde{a}$ will be triangular, and if $a_2$ and $a_3$ are equal, it will be triangular.

Consider cutting a fuzzy number as follows:

$$r-cut\ \tilde{a} : a_r = \left\{ x \in R \,\middle|\, \mu_{\tilde{a}}(x) \geq r \right\} \tag{34}$$

Since $\mu_{\tilde{a}}(x)$ is assumed to be continuous, then interval $a_r$ is closed and finite and can be written as follows:

$$a_r = \left[ f_a^{-1}(r), g_a^{-1}(r) \right] \tag{35}$$

Thus, two important concepts used in this method can be defined. The first concept is the expected interval (EI) of a fuzzy number, which is defined as follows (Heilpern, 1992):

$$EI(\tilde{a}) = [E_1^a, E_2^a] = \left[ \int_0^1 f_a^{-1}(r)dr, \int_0^1 g_a^{-1}(r)dr \right] \tag{36}$$

And the second concept is the expected value, which is written as follows:

$$EV(\tilde{a}) = \frac{E_1^a + E_2^a}{2} \tag{37}$$

Therefore, the expected value for the trapezoidal and triangular fuzzy number $\tilde{a}$ is defined as equations (38) and (39), respectively:

$$EV(\tilde{a}) = \frac{a_1 + a_2 + a_3 + a_4}{4} \tag{38}$$

$$EV(\tilde{a}) = \frac{a_1 + 2a_2 + a_3}{4} \tag{39}$$

Also, in this method, a suitable ranking method is used to defuzzificated the constraints of a possibility model (Jiménez, 1996). According to this method, for each pair of fuzzy numbers $\tilde{a}$ and $\tilde{b}$, the degree of greater than or equal to $\tilde{a}$ than $\tilde{b}$ is defined as follows:

$$\mu_M(\tilde{a}, \tilde{b}) = \begin{cases} 0 & \text{if} \quad E_2^a < E_1^b \\ \dfrac{E_2^a - E_1^b}{E_2^a + E_2^b - E_1^a - E_1^b} & \text{if} \quad 0 \in \left[ E_1^a - E_2^b < 0, E_2^a - E_1^b > 0 \right] \\ 1 & \text{if} \quad E_1^a > E_2^b \end{cases} \tag{40}$$

Now, if $\mu_M(\tilde{a},\tilde{b}) \geq \beta$ and $\beta \in [0,1]$, we say $\tilde{a}$ is at least greater than or equal to $\tilde{b}$, and we write:

$$\tilde{a} \geq_{\beta_2} \tilde{b} \equiv \frac{E_2^a - E_1^b}{E_2^a + E_2^b - E_1^a - E_1^b} \geq \beta \Rightarrow \beta E_1^a + (1-\beta)E_2^a \geq \beta E_2^b + (1-\beta)E_1^b \tag{41}$$

Similarly, the concept of equality of two fuzzy numbers $\tilde{a}$ and $\tilde{b}$ with degree $\beta$ is defined as follows:

$$\tilde{a} \text{ is indifference to } \tilde{b} \text{ in a degree } \beta \equiv \tilde{a} \approx_{\beta} \tilde{b} \text{ if we have: } \tilde{a} \geq_{\beta/2} \tilde{b} \text{ and } \tilde{a} \leq_{\beta/2} \tilde{b} \tag{42}$$

Therefore, the potential constraints are defuzzificated in unequal and equal forms as the following, in which $\beta$ is the minimum acceptable degree for possibilistic limitations and is determined by the decision-maker:

$$\tilde{a}_i x \leq \tilde{b}_i \quad \forall i \Rightarrow \left((1-\beta)E_1^{a_i} + \beta E_2^{a_i}\right)x \leq \left((1-\beta)E_2^{b_i} + \beta E_1^{b_i}\right) \tag{43}$$

$$\tilde{a}_i x \geq \tilde{b}_i \quad \forall i \Rightarrow \left((1-\beta)E_2^{a_i} + \beta E_1^{a_i}\right)x \geq \left((1-\beta)E_1^{b_i} + \beta E_2^{b_i}\right) \tag{44}$$

$$\tilde{a}_i x = \tilde{b}_i \quad \forall i \Rightarrow \begin{Bmatrix} \left((1-\frac{\beta}{2})E_2^{a_i} + \frac{\beta}{2}E_1^{a_i}\right)x \geq \left(\frac{\beta}{2}E_2^{b_i} + (1-\frac{\beta}{2})E_1^{b_i}\right) \\ \left(\frac{\beta}{2}E_2^{a_i} + (1-\frac{\beta}{2})E_1^{a_i}\right)x \leq \left((1-\frac{\beta}{2})E_2^{b_i} + \frac{\beta}{2}E_1^{b_i}\right) \end{Bmatrix} \tag{45}$$

In the above inequalities, the $E_1^a, E_2^a$ values are called as the expected range of a fuzzy number and are calculated for the fuzzy triangular numbers as the following:

$$EI(\tilde{a}) = [E_1^a, E_2^a] = [\frac{1}{2}(a_1 + a_2), \frac{1}{2}(a_2 + a_3)] \tag{46}$$

If each of the fuzzy values is mentioned in the modeling and possesses a distribution of triangular possibility and is defined as the following:

$$\tilde{Br}_{ikf} = \left(Br_{ikf}^1, Br_{ikf}^2, Br_{ikf}^3\right) \qquad \tilde{W}_{ikft} = \left(W_{ikft}^1, W_{ikft}^2, W_{ikft}^3\right)$$

$$\tilde{\theta}_{im} = \left(\theta_{im}^1, \theta_{im}^2, \theta_{im}^3\right) \qquad \tilde{\theta}_{in} = \left(\theta_{in}^1, \theta_{in}^2, \theta_{in}^3\right)$$

$$\tilde{O}_m = \left(O_m^1, O_m^2, O_m^3\right) \qquad \tilde{\alpha}_{ikf} = (\alpha_{ikf}^1, \alpha_{ikf}^2, \alpha_{ikf}^3)$$

The definitive model of the objective function (3) can be defuzzificated as follows:

$$Max \ Z_3 = \sum_{m \in M} \left( \frac{O_m^1 + 2O_m^2 + O_m^3}{4} \right) P_m \tag{47}$$

In addition, uncertain constraints are determined as follows:

$$\sum_{i \in I} \sum_{k \in K} \sum_{f \in F} \sum_{t \in T} \left( (1-\beta) E_1^{W_{ikft}} + \beta E_2^{W_{ikft}} \right) ZZ_{ikft} \le R \tag{48}$$

$$\sum_{k \in K} \sum_{f \in F} \left( (1-\beta) E_2^{\theta_{im}} + \beta E_1^{\theta_{im}} \right) G_{ikfmt} \ge D_{imt} \qquad \forall i \in I, m \in M, t \in T \tag{49}$$

$$\sum_{f \in F} \left( (1-\beta) E_2^{\theta_{in}} + \beta E_1^{\theta_{in}} \right) E_{ifnt} \ge D'_{int} \qquad \forall i \in I, n \in N, t \in T \tag{50}$$

$$\sum_{m \in M} \left( (1-\beta) E_2^{O_m} + \beta E_1^{O_m} \right) P_m \ge O^{\min} \tag{51}$$

$$\sum_{k \in K} \sum_{f \in F} \left( (1-\beta) E_2^{Br_{ikf}} + \beta E_1^{Br_{ikf}} \right) G_{ikfmt} \ge Br^{\min} D_{imt} \qquad \forall i \in I, m \in M, t \in T \tag{52}$$

$$\sum_{i \in I} \sum_{k \in K} V_{ikft} \Big/ \left( (1-\beta) E_1^{\alpha_{ikf}} + \beta E_2^{\alpha_{ikf}} \right) \le F_f \qquad \forall f \in F, t \in T \tag{53}$$

### C. Augmented Epsilon Constraint (AEC) Method

Different approaches have been proposed to solve multi-objective decision making (MODM), including the Augmented Epsilon Constraint (AEC) method. The general form of a (MODM) problem is as follows:

$$\begin{aligned} & Min (f_1(x), f_2(x), ..., f_n(x)) \\ & x \in X \end{aligned} \tag{54}$$

In the AEC model, the first objective function is constrained as the main objective, and the other objectives are constrained as the upper bound of epsilon, and the following model is replaced in which $s_i$ are the nonnegative variables for the slack, and the parameter $\phi_i = \frac{R(f_1)}{R(f_i)}$ is considered for normalizing the value of the first objective function relative to the objective *i*. In order to better implement the AEC method, the acceptable range of epsilons can be obtained using the lexicographic method (Marotas, 2009).

$$\begin{aligned} & Min \ f_1(x) - \sum_{i=2}^{n} \phi_i s_i \\ & S T. \\ & f_i(x) + s_i = \varepsilon_i^l \qquad \forall i = 2,3,...n \\ & x \in X \\ & s_i \ge 0 \end{aligned} \tag{55}$$

In the proposed model the objective function of cost is expressed as the function $f_1(x) = obj_1$ and other functions are demonstrated as constraints under the equations $obj_2 + s_2 = \varepsilon_2^l$ and $obj_3 + s_3 = \varepsilon_3^l$ .

In order to calculate the vector $\varepsilon_i^l$ , the lowest and highest values of the *k*th objective functions are calculated using the payoff table and are displayed as $f_k^{\min}$ and $f_k^{\max}$ . Then, the distance between the values of the *k*th objective function and the value of $\varepsilon_k^l$ can be calculated as follows:

$$r_k = f_k^{\max} - f_k^{\min}; \quad \varepsilon_k^l = f_k^{\max} - \frac{r_k}{q_k} \times l; \quad \forall k \neq i, l = 0,...,q_k \tag{56}$$

Where, $q_k$ is the number of distances desired by the decision-maker.

## VI. CASE STUDY

The proposed model in the present study has been investigated as a case study in Hamedan province of Iran. This province has been considered as the case study due to its acceptable capacity for cultivating Solanaceae in the seasons of the year and the construction of a significant number of greenhouses by the government in the province. Three greenhouses in regions around the province have been selected as the greenhouses for cultivating the seedling. Four manufacturing plants, including Sahar Food Factory, have been considered as candidate factories for the development of production lines. The developed lines of factories include production lines for sauces, pickles, spices, chips, and non-meat canned foods, depending on the needs and infrastructure of the factory. Two farmer's markets have been considered, one of which was located in the capital of the province and the other in one of the suburbs with an acceptable population. Furthermore, the Hamedan province and the surrounding provinces have an average share of 12% in unemployment.

### *A. Numerical Results*

The purpose of the case study is to provide an executive plan during the planning horizon of the first six months of the year, which is divided into three periods in accordance with the cultivation and harvesting period. The number of candidate factories, agricultural lands, greenhouses, and farmer's markets is equal to 4, 4, 3, and 2, respectively. The area of each greenhouse is equal to 1 hectare, and the area of each land equals 15, 18, 14, and 15 hectares, respectively. The minimum unemployment rate in the province has been estimated to be 6% and the start-up costs and employment rate developed by each factory has been measured according to the developed lines and the number of recruited personnel. The Brix of tomato is different in terms of the cultivation method and the rate of irrigation, and it has been consulted with agricultural engineers to extract the related data. The minimum Brix required for the production of tomato paste is in the range of 25-33%, which has been indicated by the distribution of the triangular possibility. The rate of product deterioration has been estimated in the fuzzy form with regards to the cultivation season, tolerance rate of crops, and distance traveled by the shipping machinery. The costs related to the shipping of products and the amount of gasoline used have been extracted from the shipping organizations, and the conversion coefficient of gasoline to carbon has been estimated to be 2.62, according to the article of Wang et al. (2019). Other input data such as water consumption, ideal yield of the land, and the costs of cultivating the products have been extracted according to the comments of experts in this field (farmers and agricultural engineers) and reliable websites in the field of agriculture and the demand for each product has been provided based on the information extracted from the Ministry of Agriculture of the province.

The proposed model was solved by GAMS 24.1.2 software. If each of the objectives is addressed separately, an optimal value will be denoted to each objective function. These solutions are presented as ideal solution and will be used in subsequent calculations. The ideal solution to the present problem is equal to $Z_1^* = 1.14385 \times 10^{10}$, $Z_2^* = 1764975.52$ and $Z_3^* = 0.13$. It is impossible to obtain this answer due to the conflict between the objective functions. The response of efficiency with the minimum deviation from the ideal solution to the objectives is selected as the best solution from the values of the Pareto Front. By applying the AEC method, a set of Pareto solutions has been obtained and given in Table II. In order to select the best solution from the set of Pareto solutions, the normalized criterion of distance until to be ideal is defined as follows:

$$ID = \frac{|Z_1 - Z_1^*|}{Z_1^*} + \frac{|Z_2 - Z_2^*|}{Z_2^*} + \frac{|Z_3 - Z_3^*|}{Z_3^*} \tag{57}$$

**TABLE II. Pareto solutions of the AEC-based three-objective optimization**

| $Z_1$ | $Z_2$ | $Z_3$ | $ID$ |
|---|---|---|---|
| $2.81235\times10^{10}$ | 1789723.21 | 0.13 | 1.472 |
| $2.62910\times10^{10}$ | 1816293.164 | 0.13 | 1.336 |
| $2.31409\times10^{10}$ | 1937701.046 | 0.129 | 1.121 |
| $2.19965\times10^{10}$ | 2008569.324 | 0.123 | 1.114 |
| $2.10786\times10^{10}$ | 2079471.347 | 0.119 | 1.1046 |
| $1.96355\times10^{10}$ | 2203935.674 | 0.119 | 1.0539 |
| $1.85476\times10^{10}$ | 2269761.79 | 0.109 | 1.0684 |
| $1.73129\times10^{10}$ | 2355997.118 | 0.109 | 1.0843 |
| $1.60975\times10^{10}$ | 2488766.912 | 0.101 | 1.092 |
| $1.56437\times10^{10}$ | 2519923.015 | 0.098 | 1.09904 |
| $1.50809\times10^{10}$ | 2599921.73 | 0.098 | 1.167 |
| $1.43911\times10^{10}$ | 2665956.851 | 0.091 | 1.171 |
| $1.36347\times10^{10}$ | 2751290.33 | 0.091 | 1.186 |
| $1.33791\times10^{10}$ | 2809190.026 | 0.085 | 1.195 |
| $1.30655\times10^{10}$ | 2864027.714 | 0.085 | 1.1986 |

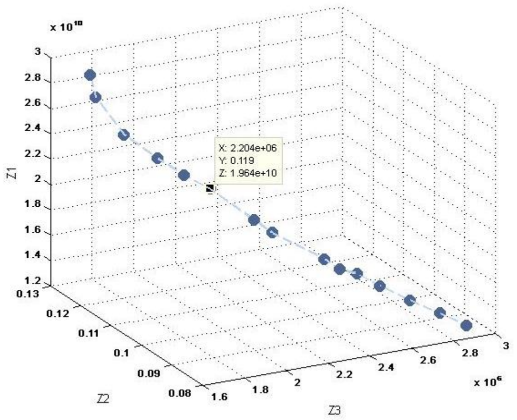


**Fig. 4. The plot of the Pareto Front and the selected solution**

Any solution with an increasing trend after deviation from the ideal solution will be considered as the best solution. Fig (4) indicates the point of the best solution for the studied problem in the Pareto Front. As shown in the figure, the optimal values of the objectives of the problem are equal to $Z_1 = 1.96355 \times 10^{10}$, $Z_2 = 2203935.674$, and $Z_3 = 0.119$, respectively.

The plots of Pareto Front of each of the objectives relative to each other are shown in Figs (5), (6), and (7), respectively. At the initial point, the optimal values of social and environmental objectives have been set, and the optimal value of cost has been calculated. Then, in the following points, the cost value has been enhanced with flexibility in social and environmental objectives.

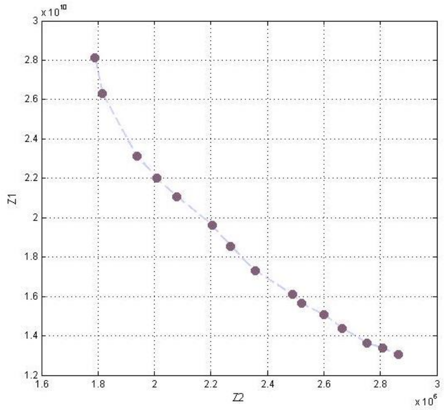


**Fig. 5. The plot of the Pareto Front of economic to environmental objectives**

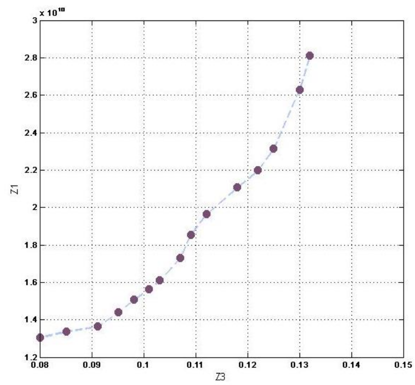


**Fig. 6. The plot of the Pareto Front of economic to social objectives**

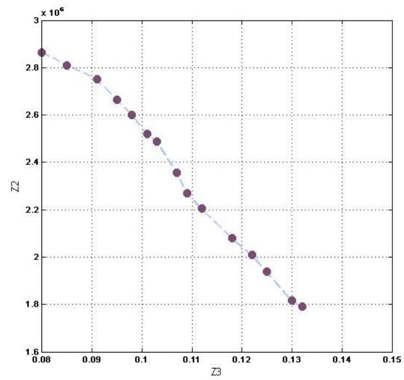


**Fig. 7. The plot of the Pareto Front of environmental to social objectives**

The solution results for the problem variables are also presented in Table III, IV and V, indicating the decision variables of greenhouses, agricultural land, and the amount delivered to factories and farmer's markets, respectively.

**TABLE III. Optimal value of the decision variable of greenhouses**

| $X_{ijt}$ (ton) | *T=1* | *T=2* | *T=3* |
|---|---|---|---|
| Greenhouse 1 | 800 | 12000 | 800 |
| Greenhouse 2 | 5000 | 500 | 10900 |
| Greenhouse 3 | 1300 | 1800 | 1300 |

bell pepper eggplant

potato tomato

According to the results in Table III, greenhouse 1 will nurture eggplant and tomato seedling during the cultivation period. Greenhouse 2 provides tomato, and bell pepper seedling and greenhouse 3 supplies the needed seedling for eggplant and bell pepper. According to the results, nurturing seedlings of each product has been done in each period, but the seedling of potato crop has not been nurtured due to being not economically affordable, because the cultivation of potato is not bush-based and providing the required conditions for nurturing its seedling is extremely expensive.

**TABLE IV. Optimal value of the decision variable of agricultural lands**

| $V_{ikft}$ $(ton)$ | Land 1 | | | Land 2 | | | Land 3 | | | Land 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 |
| K=1 | 800 | 500 | 800 | 5000 | 1800 | 1300 | 1300 | - | 10900 | - | 12000 | - |
| K=2 | 2200 | 1200 | 2200 | 10000 | 602 | 400 | 400 | 4000 | 2054 | 5000 | 1955 | 4824 |

The results in Table IV show the amount of each product to be harvested according to their cultivation method. For instance, in the first agricultural land and the first period, eggplant has been cultivated and harvested by two methods. One part of the product (800 tons) has been cultivated with nurtured seedling, and the other part (2200 tons) has been cultivated using seed composition and irrigation method. Furthermore, in the case of third agricultural land, it can be stated that the only potato has been cultivated and harvested in the second period. It should be noted that only first and second methods have been applied in the proposed model considering the cost of cultivation. It is also obvious from the results that the crop rotation policy has been properly observed. Table V shows the amount of product to be delivered to factories and farmer's markets.

**Table V. The optimal value of the decision variable of delivering to factories and farmer's markets**

| | $G_{ikfmt}$ $(ton)$ | | | | | | | | | $E_{ifnt}$ $(ton)$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Factory 1 | | | Factory 1 | | | Factory 1 | | | Farmer market 1 | | | Farmer market 2 | | |
| | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 | T=1 | T=2 | T=3 |
| F=1 | 800 | 490 | 800 | 675 | 370 | 630 | 700 | 450 | 780 | 420 | 220 | 420 | 310 | 170 | 350 |
| F=2 | 4100 | 700 | 510 | 3800 | 570 | 360 | 3800 | 610 | 460 | 1800 | 330 | 210 | 1600 | 270 | 160 |
| F=3 | 370 | 1140 | 3420 | 400 | 1020 | 3400 | 450 | 900 | 2900 | 270 | 640 | 2400 | 190 | 500 | 1900 |
| F=4 | 1360 | 3600 | 1170 | 960 | 4300 | 1020 | 1160 | 3500 | 970 | 960 | 1800 | 670 | 760 | 1600 | 530 |

Table V indicates the amount to be delivered to the third level of the supply chain for the purpose of estimating the demand for the shown products. According to the presented results, each of the agricultural lands has cultivated some products, and in addition to focusing on the costs of cultivation and harvesting, they have also paid attention to the issue of preserving environmental resources such as water and soil, which indicates the proper functioning of the model in addressing the sustainability dimensions.

Comparing the results of the model with the total amount of cultivated crops in the four studied agricultural lands over the past three years, the efficiency of the proposed model is evident due to better exploitation of lands, as shown in Fig (8). The diagram of the annual harvest indicates that the use of the proposed model enables stakeholders to obtain a higher harvest compared to the average of the last three years. The increase of harvested amounts of each crop (potatoes: 12%, tomatoes: 9.6%, bell peppers: 31%, eggplant: 9.5%) suggests that the use of different cultivation and crop rotation policies has resulted in better exploitation of agricultural lands throughout the planning horizon, which has led to approaching the ideal yield factor of agricultural lands while maintaining the sustainability and reducing the water consumption. This increase the yield of agricultural lands results in higher farmers' satisfaction, because they are able to benefit more and can even apply more balanced pricing on crops by efficient use of land and water resources, and consequently the reduction of water consumption.

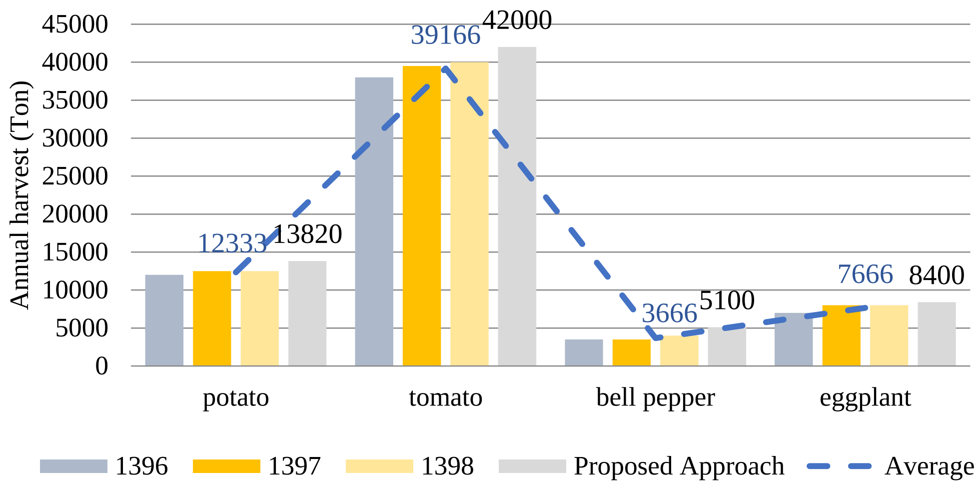


**Fig. 8. The comparison of annual cultivation in all agricultural lands over the past three years**

On the other hand, in order to show the efficiency of the model in terms of saving water consumption, a comparison has been made based on the amount of water consumption according to the proposed model and conventional agriculture. For this purpose, the water consumption of one ton of products has been calculated and shown in Table VI using the equations as follows:

Real water consumption of one ton of the product $(\frac{\mathrm{m}^3}{ton})$ =

Amount of production by the conventional method in one hectare*W $(\frac{\mathrm{m}^3}{\mathrm{hectare}})$/Total production

Water consumption of one ton of the product according to the model $(\frac{\mathrm{m}^3}{ton})$ =

Amount of production according to the model in one hectare*W $(\frac{\mathrm{m}^3}{\mathrm{hectare}})$/Total production

**Table VI. The comparison of water consumption in conventional mode and the proposed approach**

| | *Tomato* | *Eggplant* | *Bell Pepper* | *Potato* |
|---|---|---|---|---|
| Water consumption $\frac{m^3}{ton}$ (Conventional method) | 32.53 | 107.625 | 237.66 | 118.75 |
| Water consumption $\frac{m^3}{ton}$ (Proposed method) | 27.60 | 89.33 | 197.03 | 99.73 |
| Water saving percentage | 15.15% | 16.99% | 17.07% | 16.03% |

As can be seen from the results shown in Table VI and Figs (9) and (10), the saving of water consumption can be estimated by 1669092 $m^3$ (equivalent to 65.258% for all products) by comparing the amount of water consumption according to the proposed model and the conventional method used in past years. These results suggest that using the proposed model will be useful in maintaining the sustainability of water resources.

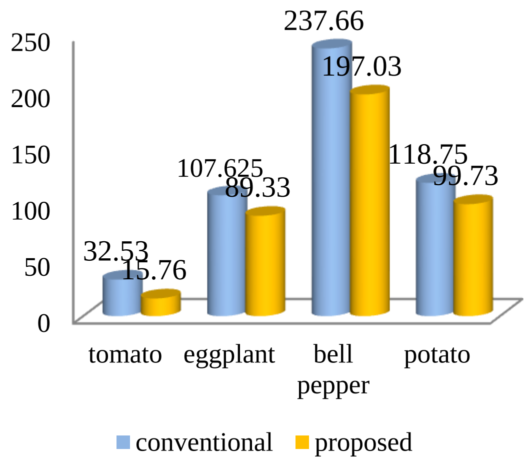


**Fig. 9. The comparison of water consumption of products according to the conventional and proposed approach**

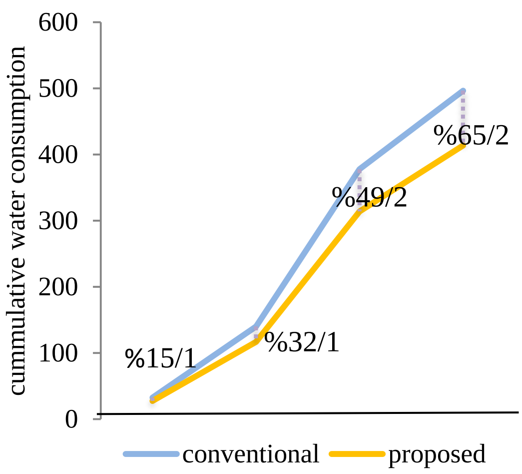


**Fig. 10. The difference between cumulative water consumption according to the conventional and proposed approach (%)**

Moreover, as the process of solving the developed model is performed using the AEC method, another solution approach is used to review the results and provide comparative analysis. Another approach to solving multi-objective mathematical models is the Weighted Sum Approach (WSA). In this method, different weights are assigned to the functions to express the importance of each function. We have three objective functions in the developed model, the equal value of $\frac{1}{3}$ is considered to be assigned to each objective function. Consequently, by assigning weights to each objective, the multi-objective model converted to a weighted single-objective (f) function. Therefore, as shown in Equation (58), the weighted sum of the objective functions is optimized (Mavrotas, 2007). Where the $W_i$ , $f_i(x)$ and S show the weights, objective functions and feasible area, respectively.

$$\max(w_1 \times f_1(x) + w_2 \times f_2(x) + \ldots w_p \times f_p(x)) \tag{58}$$

S.T.

$x \in S$

In this solution approach, considering the mentioned weights, the optimal values of the objective functions are shown in Table VII. In addition, considering that by changing the weight of the importance of the functions, different answers can be produced, therefore in Table VIII we have changed the weights of the objective functions and analyzed the results of decreasing or increasing each of the objective functions.

**TABLE VII. The total amount of harvested products from all agricultural lands**

| $Z_1$ | $Z_2$ | $Z_3$ |
|---|---|---|
| $2.18124 \times 10^{10}$ | 1991940.034 | 0.1217 |

**TABLE VIII. The total amount of crops produced by seedling cultivation**

| $W_1$ | $W_1$ | $W_1$ | Decrease $Z_1$ | Increase $Z_2$ | Decrease $Z_3$ |
|---|---|---|---|---|---|
| 0.9 | 0.05 | 0.05 | 74.8 | 59.3 | 36.7 |
| 0.8 | 0.1 | 0.1 | 74.1 | 57.8 | 36.7 |
| 0.7 | 0.15 | 0.15 | 42.33 | 33.6 | 21.42 |
| 0.6 | 0.2 | 0.2 | 41.79 | 28.13 | 21.42 |
| 0.5 | 0.25 | 0.25 | 13.45 | 15.96 | - |
| 0.4 | 0.3 | 0.3 | 4.37 | 1.3 | - |
| $\frac{1}{3}$ | $\frac{1}{3}$ | $\frac{1}{3}$ | - | - | - |
| Note: Changes are measured on the basis of equal weights | | | | | |

The results of the solution show that in comparison with the case where the supply chain is economy-oriented, when the chain managers pay attention to all three economic, environmental and social aspects (a sustainable supply chain) together, part of the profit of the chain is lost and increased costs. Thus, finding the right balance between costs, reducing the effects of greenhouse gases and increasing the employment rate is importance. Moreover, as the importance of the economic aspect decreases, the cost of the chain increases, but the supply chain is more sustainable in terms of environmental and social aspects (see Fig (11)).

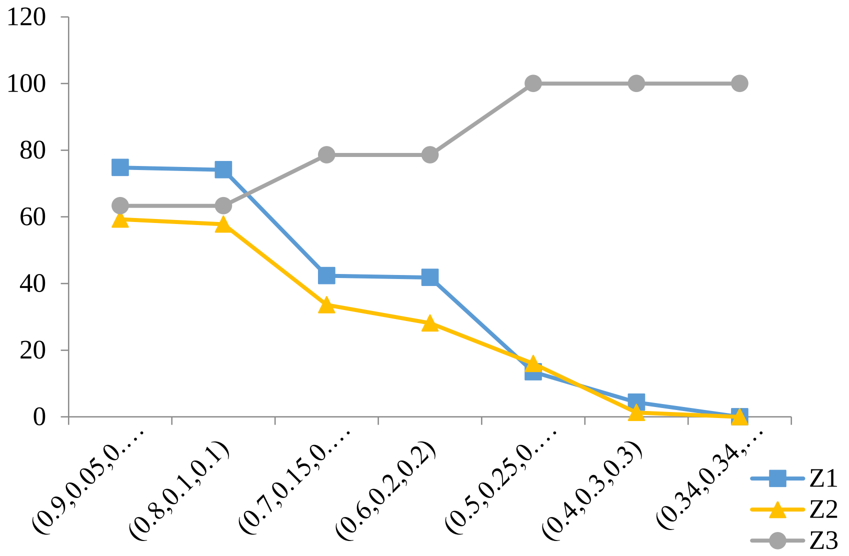


**Fig. 11. The changes in objective functions**

## VII. THE RESULTS OF LARGE SIZE

In order to solve the problem in large size, it is necessary to increase the dimensions of the problem. In this study, the dimensions of the problem have increased to the extent that it can be solved by exact method. The dimensions of the current problem have been increased by increasing the number of greenhouses, agricultural lands, factories and farmer's markets. The number of products, planting methods and planning horizon have remained unchanged due to the nature of modeling and the problem. In order to solve the model in these dimensions, the random numbers have been used as input parameters. Thus, the proposed model in high dimensions has been solved by GAMS 24.1.2 software. As stated; if each of the objectives is addressed separately, each objective function is at its optimal value. The ideal solution to the present problem is equal to $Z_1^* = 4.0234 \times 10^{11}, Z_2^* = 3161357.636,\ Z_3^* = 0.195$, given the conflict between the objective functions; this answer is not available. Using the AEC method, a set of Pareto solutions are obtained and are given in Table IX that the best solution is selected according to the least distance index.

**TABLE IX. Pareto solutions of the AEC-based three-objective optimization**

| $Z_1$ | $Z_2$ | $Z_3$ | $ID$ |
|---|---|---|---|
| $5.0467 \times 10^{11}$ | 3103247.329 | 0.195 | 1.223 |
| $4.9923 \times 10^{11}$ | 3197543.76 | 0.195 | 1.136 |
| $4.8072 \times 10^{11}$ | 3215446.03 | 0.167 | 1.101 |
| $4.7943 \times 10^{11}$ | 3356742.973 | 0.167 | 1.078 |
| $4.5701 \times 10^{11}$ | 3418956.88 | 0.167 | 1.056 |
| $4.4429 \times 10^{11}$ | 3543789.14 | 0.143 | 1.063 |
| $4.3107 \times 10^{11}$ | 3605786.77 | 0.143 | 1.117 |
| $4.1253 \times 10^{11}$ | 3826379.412 | 0.101 | 1.138 |

According to the results of solving the problem in large size, despite the increase in costs and to some extent the increase in greenhouse gas production, the amount of water consumption has decreased (see Table X) and harvest of products has increased (see Fig (12)). This issue can create a good balance in the profit from the sale of products and prevent the consumption of water resources, and thus be compensated the cost and maintained environmental sustainability. In fact, it can be said that with increasing dimensions of the problem and by using planting policies in higher dimensions, water consumption decreases. Moreover, according to Table IX with the increase of the dimensions of the problem and the construction of more production lines, the employment rate also increases, but this rate has increased in such a way that other functions can also be controlled.

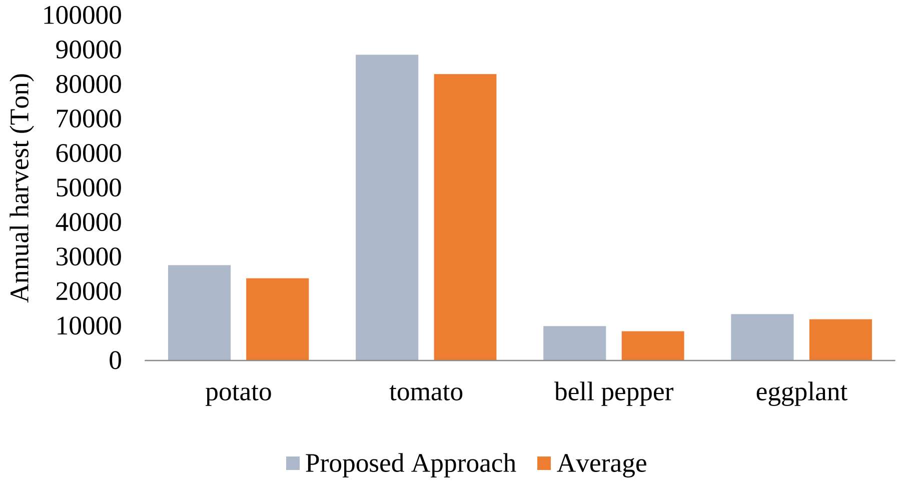


**Fig. 12. The comparison of harvests along the planned horizon and the average harvest of previous years**

**Table X. The comparison of water consumption in conventional mode and proposed approach**

| | Tomato | Eggplant | Bell Pepper | Potato |
|---|---|---|---|---|
| Water consumption $\frac{m^3}{ton}$ (Conventional method) | 32.53 | 107.625 | 237.66 | 118.75 |
| Water consumption $\frac{m^3}{ton}$ (Proposed method) | 25.89 | 80.28 | 188.93 | 97.73 |
| Water saving percentage | 20.41% | 25.4% | 20.5% | 17.7% |

## VIII. MANAGEMENT INSIGHTS

If the decision-maker intends to evaluate the efficiency of the model to meet demands by considering the policies used in this study for the purpose of estimating the possibility of export, different scenarios will occur during the increasing trend of demands. In order to study these scenarios and analyze them by keeping other parameters constant, the demand for each product has been increased by 20%, 30%, 40%, and 50%, and the results have been presented in Table XI.

**TABLE XI. The total amount of harvested products from all agricultural lands**

| Scenario | | Tomato | Eggplant | Bell Pepper | potato |
|---|---|---|---|---|---|
| Increased demand | 20% | 43500 | 8902 | 5270 | 14500 |
| | 30% | 44300 | 9150 | 5655 | 14854 |
| | 40% | 45000 | 8400 | 6040 | 15180 |
| | 50% | Infeasible | Infeasible | Infeasible | Infeasible |

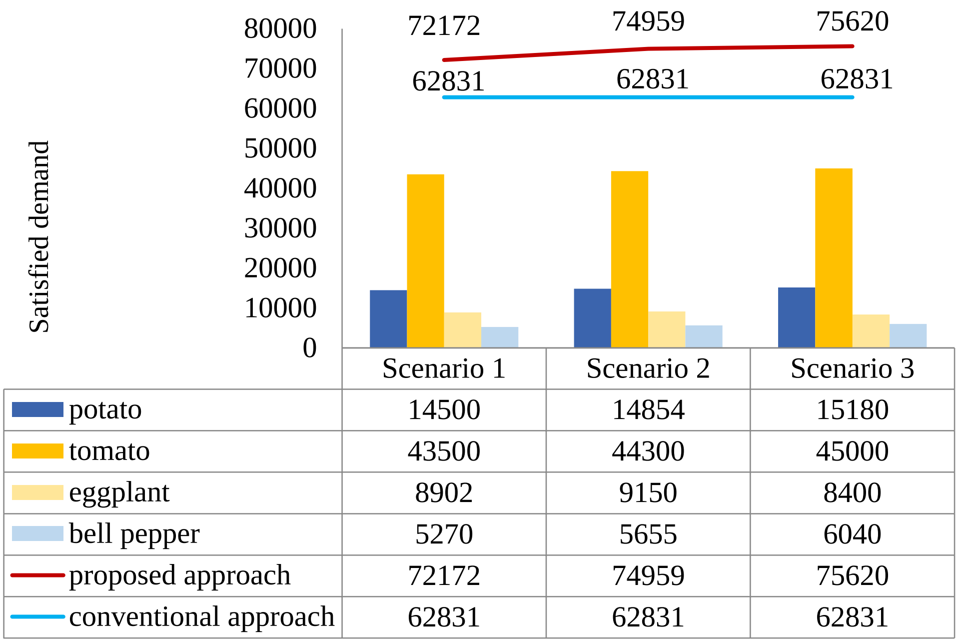


**Fig. 13. The estimation of the demand to be satisfied according to different scenarios**

The results of Table XI indicate that the proposed model will be capable of meeting the demand with an increase of up to 40%, and then, it will be infeasible. The results indicate that the use of crop rotation and different cultivation policies has caused the number of harvested products per hectare to be closer to the yield of the agricultural land, which will create the export opportunities in the long-term vision. As shown in Fig (13), the proposed model shows a significant efficiency in responding to demands compared to the average annual harvest, which enables managers to significantly increase responding to demands by implementing the proposed policies for all agricultural lands under cultivation in the region.

On the other hand, due to the limited capacity of greenhouses, the possibility of cultivating seedling will be limited; however, the benefits of using the policy of nurturing seedling in cultivating the crops and water consumption are essential. Therefore, by keeping other parameters constant, the capacity of greenhouses has been increased by 20%, 30%, 40%, and 50%, and the results have been presented in Table XII.

**TABLE XII. The total amount of crops produced by seedling cultivation**

| Scenario | | Tomato | Eggplant | Bell Pepper | potato |
|---|---|---|---|---|---|
| Increased Capacity | 20% | 29150 | 4100 | 4200 | - |
| | 30% | 32000 | 4750 | 4980 | - |
| | 40% | 32000 | 5620 | 5400 | - |
| | 50% | 32000 | 6800 | 6100 | - |

According to the results, with the increase in the capacity of greenhouses, the proposed model prefers to use seedling cultivation policy in the cultivation of products. However, the production of tomato has remained constant with the seedling cultivation policy with a more than 30% increase in the capacity of greenhouses. Furthermore, in the case of increasing the capacity of greenhouses, cultivating potato seedling is not suggested in the proposed model due to higher costs and lower yields, which indicates the proper functioning of the model.

The changes in greenhouse gases and water consumption during the alterations in greenhouse capacity and changes in the trend of cost function components at the first and second levels are indicated in Fig (14) and Fig (15), respectively. These charts show that the emissions of greenhouse gases have been raised with increasing capacity greenhouses; however, water consumption is significantly decreasing. On the other hand, production and distribution costs will increase at the first level, but the cultivation and harvesting costs will be reduced. It appears that by examining and analyzing the results, the proper decision can be made to maintain the sustainability of resources at a lower cost.

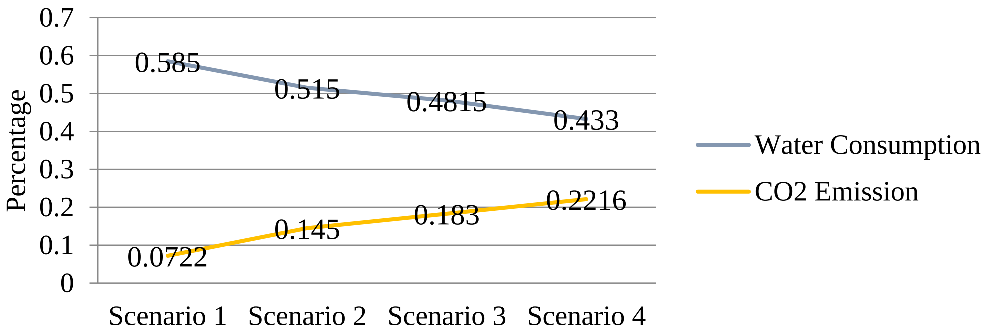


**Fig. 14. The changes in water consumption and emissions of greenhouse gases**

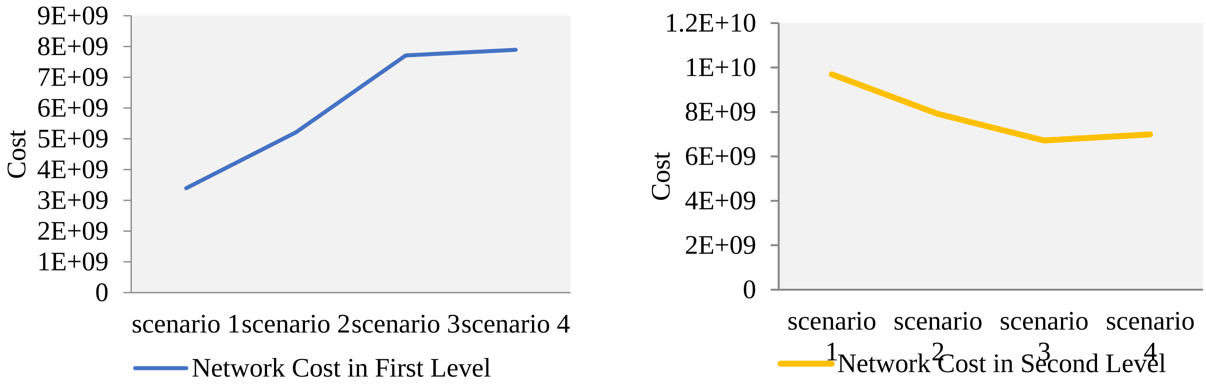


**Fig. 15. The changes in the trend of the components of the cost function by altering the capacity parameter**

Therefore the some of the industrial and managerial insights are presented as follows:

1. As it is clear from the results of the solution, the use of different planting and crop rotation policies has caused farmers to make good use of farms and has led to approaching the ideal yield factor of agricultural lands while maintaining the sustainability and reducing the water consumption. This increase in yield leads to farmers' satisfaction and they are able to gain higher profits and thus make more balanced pricing on crops, which increases the profitability of the entire supply chain.

2. Since water shortage is one of the vital issues in the country's crises, the preservation of water resources is of great importance. The use of planting policies enables agricultural supply chain managers to be able to conserve water resources while maximizing the benefits and ideal use of supply chain components and reducing greenhouse gas emissions.

3. Paying attention to the degree of Brix in the production of processed product increases food safety. The use of seedling planting policy and crop rotation leads to the production of a more desirable tomato crop with Brix degree. Therefore, considering the Brix degree causes quality products to be achieved and food safety to be increased by spending less resource on financial and environmental investments.

4. One of the vital issues in government planning is planning for youth employment and reducing the unemployment rate in developing areas. Attention to the three dimensions of sustainability leads to the preservation of natural resources and adjusting the benefits of supply chains, social responsibility to be considered by establishing factories and industrial and agricultural centers in areas with higher unemployment rates.

5. According to the analysis based on the importance of objective functions, it can be said that if decision makers in the supply chain attach relatively high importance to environmental and social criteria, the chain will no longer be economically justifiable. Therefore, the existence of incentives and financial support from governments is very effective in relieving managers' concerns about reducing chain profits and increasing their motivation to consider environmental and social criteria.

## IX. CONCLUSION

In the present study, the three-level supply chain for crops of Solanaceae has been presented considering the sustainability dimensions. In this regard, while reducing costs as an economic dimension and reducing the emission of greenhouse gases and water consumption as environmental dimensions, the employment of the population of the region has also been considered as a social dimension. In order to achieve the above-mentioned issues, a Mixed-Integer Nonlinear Programming model has been proposed with the purpose of minimizing the costs, minimizing the emissions of greenhouse gases, and maximizing employment. The crop rotation policies and different cultivation methods such as nurturing seedlings have been used instead of direct use of crop seeds and a combination of various methods of irrigation with crop seeds in order to preserve environmental resources. On the other hand, in order to increase food safety and the quality of the processed product, focusing on the Brix index has also been included in the research framework. Moreover, the parameters of the employment rate, water consumption rate, deterioration rate, and Brix of tomatoes are considered as fuzzy by maintaining the nature of uncertainty. The results of the model analysis indicate that the proposed model has reduced the unemployment rate by 11.2%, and the use of above-mentioned policies in addition to better exploitation and increasing the productivity of agricultural land, has resulted in the preservation of soil resources and reduced the water consumption by 1669092 $m^3$.

This study enables the managers of the agricultural supply chain to make more appropriate decisions at different levels of the chain by examining planting policies. This leads to the satisfaction of all components of the supply chain, including managers, farmers and customers, by harvesting quality products, increasing the yield of agricultural lands, and creating a sustainable supply chain. On the other hand, paying attention to the sustainability dimensions enables managers to pay attention to environmental sustainability and social requirements while reducing costs.

For the purpose of research development, the import and export rates of products can be considered. It is also possible to apply fully deteriorated products as organic fertilizers in the agricultural supply chain by implementing reverse logistics. On the other hand, concentrate factories can be added to the supply chain and guided to these factories with a percentage of deterioration rates of products.

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