Journal of Industrial and Systems Engineering
Vol. 14, No. 4, pp. 234-269
Autumn (November) 2022

JISE

Designing a closed-loop supply chain network with a combined algorithm solution method: A case study of pomegranates

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Abstract

The competitive environment in the global market makes most countries look for better ways to solve problems in order to earn more money. One of the strategies proposed as a competitive one is to use a stable closed loop to improve performance. The present study, which has not reported any research in this field, proposes a multi-level sustainable chain-loop supply chain (SCLSC) network for pomegranate fruit. The mathematical model has been designed with the aim of offering the lowest price, the amount of response received and the reduction of costs. Our study distinguishes itself from other studies by considering the costs of using artificial intelligence in the production chain and in the reverse logistics sector, converting pomegranate waste into recycled products including ethanol for car fuel and organic fertilizer production. In order to examine the research gap and approach real-world applications, an applied example in Iran has been studied. Also, NSGA-II and MOPSO algorithms are used to solve the model, and in the new solution method, the HSA&TS multi-objective hybrid algorithm is proposed. In addition, in the comparison of algorithms, indicators in the one-way variance analysis table, the best time is $\boldsymbol{\mu}_{\text{HSA\&TS}}^{\boldsymbol{Time}} = 641$. Therefore, the practical result show that the combined development algorithm of HSA&TS is a suitable technique and it is superior to other selected methods, it is also recommended, usable and implementable for the development of the logistics network.

Keywords: supply chain, sustainable closed loop, pomegranate waste, ethanol, novel solution

1- Introduction

In today's market, the management of returns is a complex issue that requires decisions at both strategic and operational levels. The major tasks to do at the strategic level include determining the type of the required facilities and their location, controlling the amount of the returned materials, and planning the flow of those materials (Gholipour et al. 2023). Designing supply chain networks plays an important role in supply chain management. It involves determining the location of factories and distribution centers as well as the means of transportation for the production and delivery of products to customers (Tan et al. 2019). Nowadays, environmental damage is usually more important than the costs incurred to collect the returned products. As its name suggests, reverse logistics (RL) has to do with the flow of returned products, while closed-loop supply chains CLSCs deal with both forward and reverse flows. Therefore, they are partly different concepts; a CLSC is, indeed, a comprehensive network including RL and forward logistics. Researchers have mentioned that it is a tool to create more value for all the stakeholders in a supply chain.

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ISSN: 1735-8272,

An important reason for implementing RLs is environmental protection (Cheraghalipour et al. 2018). The lack of comprehensive management and information systems and application models in the supply chains of agricultural food products in Iran has made the agriculture sector inefficient despite its potentials. One of the country's biggest problems in the agriculture and food sector is the lack of farmers' awareness of the balanced and demand-based cultivation of agricultural products. Any disturbance of this balance, on the one hand, causes the abundance of products and a significant decrease in their price in one year, which harms the farmers. On the other hand, the reduction of other products causes an increase in the price. High prices and people's dissatisfaction make it necessary to devise logistic models in the agriculture and food sector (Takavakoglou et al. 2022). Defective products and wastes have always been a significant challenge for agricultural producers. They have found that product recycling, i.e., reusing product wastes and residues, not only reduces harmful effects on the environment but also improves competitiveness in the market. From this perspective, organizations in the field of recycling and logistics have focused on creating closed-loop supply chains. These structures can achieve economic, social and environmental goals at the same time (Chobar et al. 2022).

An agricultural food supply chain (AFSC) is a well-organized system that includes raw material producers, processors, distributors, and consumers (Borodin et al. 2016) and (Utomo et al. 2018). In recent years, the agri-food industry, in general, and the fruit sector, in particular, have been recognized in supply chains as a key concept for competitiveness. Moreover, access to fresh fruits, fruit quality, food quality, and year-round access to farming products have gained enough significance to increases the demand for those products led to the recognition of agriculture as the most important sector of the economy in the future (Tsolakis et al. 2014). In addition, increased consumer awareness has brought food safety into the focus of consumers and producers. Improving food quality control is, thus, an important purpose in food cooperation, and quality assurance is significant for making profits (Hu et al. 2019). Based on the points discussed, this study presents a new model for agricultural food supply chains. The proposed model regards the design of a closed-loop supply chain for pomegranates. Pomegranate, as a highly demanded fruit, is one of the main agricultural exports in some countries. The places where pomegranates thrive usually have certain centers established for processing the fruit, thus contributing to employment and income.

The waste of food articles is a big challenge facing the food security in the world. For example, according to the Food and Agriculture Organization (FAO), in the industrial processing of pomegranates, approximately 1.5 million tons of waste is produced annually, which has a great nutritional value (Zandbiglari et al. 2021). One of the main methods of processing organic waste is to recycle waste into vermicompost, which helps to preserve the environment and public health while producing a significant amount of a valuable organic fertilizer. Vermicompost is an organic bio-fertilizer obtained through the rapid and stable transfer of organic matter from the digestive tract of a specific species of earthworms and the excretion of the substance from their bodies (Abolfazli et al. 2022) and (Tambe, 2014). Designing the facilities and equipment necessary for the production of vermicompost is of concern in the present study. It is also possible to extract ethanol from pomegranate skin and pomegranate waste (Saleem et al. 2020), which is of various applications such as automobile fuel (Pourghader Chobar et al. 2021) and (Bayanati et al. 2022). The production of ethanol from pomegranates is a distinctive feature of this study. In addition, the ability to combine computer vision with artificial intelligence algorithms in agriculture is significant (Pourghader chobar et al. 2022). Computer image processing and vision applications have flourished due to reduced equipment costs, enhanced computing power, and increased interest in food evaluation methods (Mahajan et al. 2015). These techniques offer advantages over traditional methods that are based on manual work (Barbedo, 2016). Using them in production to increase the quality of the final product following food safety standards is economically efficient (Pourghader chobar et al.2022) In order to reduce the damage caused by pests and decay before harvesting, rotten and infected fruits are identified by image processing (Khaje Zadeh et al. 2021), and they are delivered from the garden to the compost center to be turned into a fertilizer (Cheraghalipour et al. 2018). In this regard, the proposed model is designed to minimize the supply chain costs, maximize the response to customer demand and reduce the supply risks. In order to delineate the problem and get close to real-world programs, a practical example has been studied in Iran. In addition, the proposed model is solved with exact methods and a meta-heuristic algorithm.

The research questions are as follows:

- Where are the distribution centers', recycling centers and factories to be established, and how much is the flow between the established centers?
- Will reverse logistics lead to profitability in Iran's pomegranate industry?
- How can pollution and losses be reduced by implementing this plan in an inclusive mode?

The research objectives are as follows:

- Designing a sustainable multi-level closed-loop network including producers, distributors, customers, compost centers, compost customers and factories, and the customers of food and energy
- Processing pomegranate waste, such as separating the skin from the other parts to produce compost or ethanol
- Using the NSGA-II, MOPSO and HSA&TS algorithms to solve the mathematical model and comparing their performances.

The rest of this article is organized as follows. Section 2 provides a review of the relevant literature. In section 3, a mathematical model is proposed. The solution methods are discussed in Section 4. Section 5 presents the designed pomegranate supply chain in Iran as a problem. In Section 6, the problem is solved using the NSGA-II, MOPSO and HSA&TS algorithms. Section 7 analyzes and compares the algorithms based on the indices obtained. Finally, Section 8 provides the conclusion of the study and makes suggestions for future research.

2- Literature review

Considering the acceleration in the industrialization of agriculture, the increase in global food demand, and concerns about the quality and safety of food (Mangla et al. 2018), the current research aims at supply chains of perishable garden products. Various studies have been conducted on pomegranates, but there has been no research on supply chains for pomegranates. The popularity of pomegranates and the willingness of consumers to pay whatever price signify the considerable demand for pomegranate and their derivatives. This has made producers focus on the market further (Zandbiglari et al. 2021). It has also led to increasing global competition for producing and exporting pomegranate products (table 1).

Supply chain management plays an important role to optimize production costs in competitive markets (Jahangiri et al. 2021). Public awareness has also raised the attention paid to reverse logistics (RL) and closed-loop supply chain (CLSC) issues (Dowlatshahi, 2000). In addition, the importance of RL leads more companies to use it as a strategic tool for economic benefits and social image (Kannan et al. 2012). Companies have realized that implementing the mechanisms of product returns and effective RL can provide a competitive advantage (Stock and Mulki, 2009). So far, a lot of research has been conducted in this respect. For example, RL operations were studied for their possible benefits in the publishing industry (Wu and Cheng, 2006). Moreover, the problems of RL operations in the electronics industry were detected and studied in China (Lau and Wang, 2009). In another attempt, e-waste reverse logistics in Brazil was analyzed with strategic options (Guarnieri et al. 2016). In order to design a closed-loop supply chain, Fleishman et al. (2001) proposed a linear integer program. Similarly, et al. (2022) implemented a case study of the mentioned network in Germany. Another study of closed-loop supply chain networks was done by Cheragalipour et al. (2018). Focusing on citrus fruits, they developed a single-product, multi-period and dual-objective mathematical planning model. Due to the computational complexity of real problems, meta-heuristic multi-objective algorithms were developed. The results of investigating the model efficiency showed that the proposed approach could be used for the development of a citrus logistics network. Wang and Hsu (2010) solved a closed-loop model using a genetic algorithm based on a tree structure. For further examples, Table 2 presents some review studies in the field of RL and CLSC.

Table 1. Estimation of global pomegranate production and export of some countries

Country	Planted aera(ha)	Production(t)	Export(t)
Iran	65000	600000	60000
India	54750	500000	22000
Chaina	Unknown	260000	Unknown
USA	6070	110000	17000
Turkey	7600	90000	Unknown
Spain	2400	37000	14000
Tunisia	2600	25000	2000

Table 2. The studies reviewed in the field of RL and CLSC

Paper		Area	Scope	Time scope
1	Souza (2013)	CLSC	strategic and tactical decisions in CLSC	1978–2012
2	Govindan et al. (2015)	RL & CLSC	SCND under uncertainty	1995-2015
3	Jena and Sarmah (2016)	CLSC	Acquisition management in CLSC	2000-2014
4	Wang et al. (2017)	RL	The whole area in RL	1992-2015
5	Dialo et al. (2016)	CLSC	Quality, reliability and maintenance issue in CLSC	1990-2016
6	Govindan and Soleimani (2017)	RL & CLSC	The whole area in RL & CLSC	2001-2014
7	Coenen et al. (2018)	CLSC	Complexity and uncertainty in CLSC	2012 – 2017
8	Barz et al. (2018)	CLSC	The bullwhip effect in CLSC	2004-2018
9	Kazemi al. (2019)	RL & CLSC	The whole area in RL & CLSC	2000 – 2017
10	MahmoumGonbadi et al.(2021)	CLSC	A bibliometric and content analysis of 254 papers in CLSC	2000 – 2019

2-1- Agriculture food supply chain (AFSC)

Agricultural food supply chain (AFSC) management is a rapidly evolving field of research (Tsolakis et al. 2014). Significant amounts of fresh agricultural products, especially fruits, are wasted at various operational levels of agricultural supply chains. The modeling of the key factors leading to post-harvest losses of fruits and vegetables in the supply chain of fresh agricultural products was investigated by Anand and Barua (2022). An important challenge of hybrid modeling for the supply chain network of Colombian organic perishable coffee was investigated by Clavijo-Buritica et al. (2022). The integrated planning of multipurpose production and distribution of perishable products was done by Amorim et al. (2012). In an extensive review, Nematollahi and Tajbakhsh (2020) presented the past, present and future issues of sustainable agricultural supply chains derived from 247 quantitative studies. The main feature of this study was the focus on perishable and fresh products. One of the first studies that focused on agriculturally diverse, perishable, and unpredictable foods as well as vegetables was conducted by Ahumada and Villalobos (2009) who also simulated models for agricultural supply chains (ASC). A summary of the studies from 1991 to 2011 on fresh food products and flowers was provided by Shukla and Jharkharia (2013). The main feature of their study was the focus on perishable and fresh products. A CLSC network was designed with certain social factors and two goals including the minimization of total costs and the maximization of employment in different locations. In order to validate the proposed model, a case study was done in the avocado industry in Puebla, Mexico (Salehi-Amiri et al. 2022). Table (3) presents some studies on the supply chains of agricultural products.

According to the literature review, the research gap is the lack of attention to closed-loop networks for certain food products and mechanisms for processing pomegranate waste, such as separating the skin from other parts. The mathematical model proposed in this study is a comprehensive model intended to compensate the shortcomings of other works by using the variables of decision-making at harvesting, production, distribution, and inventory levels. Moreover, due to the complexity of the proposed problem, multi-objective and combined algorithms are used especially in large dimensions. For more efficiency, a case is done along with numerical examples, and the applied algorithms are compared in terms of performance.

2-2- A review of studies on pomegranates

Pomegranate is one of the oldest known edible plants originating in Central Asia. Its wide global geographical distribution nowadays reflects its adaptability to various climatic conditions. It is important for its nutritional, medicinal and ornamental properties, high demand, and industrial value. Da Silva et al, (2013) presented a basic biological account of plants and how to use biotechnological tools. In a sensitivity analysis of the energy input and economic value of pomegranate production in Iran, Troyjani (2018) investigated the amount of energy consumption and costs of pomegranate production in Mazandaran Province. Chalchami and Dinakaran (2015) conducted a comparative study on the concentration of vermicompost from the wastes of pomegranate and sweet lemon using a type of earthworm. Wang et al. (2012) showed that pomegranate juice is a natural product that inhibits prostate cancer progression. Lee et al. (2006), evaluated the antioxidant properties of pomegranate peel extract compared to those of pomegranate pulp extract. Sheydaei et al. (2012) analyzed the correlation between the geography and the cytogenetic diversity of pomegranate cultivars. According to Karimi et al. (2017), pomegranate is a promising opportunity in medicine and nanotechnology. They studied different parts of pomegranate as well as its properties, chemical compounds, antibacterial effects, medicinal applications and anti-cancer properties. The research conducted by Braga et al. (2005) in Brazil indicated that pomegranate extract inhibits the growth of staphylococcus aureus and the subsequent production of enterotoxin. The grading and identification of diseases in pomegranate leaves and fruit were performed by Deshpande et al. (2014). Their innovative technique is useful to many people and has many advantages over the traditional grading method. An example is the use of information and communication technology (ICT) in agriculture, which ultimately contributes to the precision of agricultural methods. Akin et al. (2012, August) investigated the recognition of pomegranates on the tree using image processing. Moreover, Demirai (2018) indicated that pomegranate peel is a promising raw material for second-generation ethanol production. Instead of being thrown away as agricultural and industrial waste, pomegranate peel (as an abundant by-product of the fruit juice industry) becomes a value-added product such as ethanol. In addition, the production of citric acid from pomegranate peel was studied by Rokas and Kutskidou (2020). According to them, using inexpensive crop residues through solid-state fermentation can help to achieve an industrially and environmentally sustainable method of producing citric acid.

Table 3. The literature on agriculture: A comparison of previous studies and the current study

Authors /year	**Type of product**	**Modeling**	**Type of model**	**Solution method**	**Objective function**	**Scope**	**Example**
Homayounfar, M., & Daneshvar (2018)	Olive	Linear programming	Multi-objective optimization	Exact	Minimize transportation costs	Application of fuzzy optimization to a supply chain network design	Case
Asgari et al. (2013)	Wheat	Integer linear programming	Single-objective optimization	Exact	Minimize transportation costs	Developing model-based software to optimize wheat storage and transportation	Numerical
Nadal-Roig and Plà-Aragonés (2015)	Fruits	Linear programming	Single-objective optimization	Exact	Minimize transportation costs	Optimal transport planning to supply a fruit logistic centre	Case
Etemadnia et al. (2015)	Fruits and vegetables	Mixed integer linear programming	Single-objective optimization	Heuristics	Minimize the total cost	Optimal wholesale facilities location within the fruit and vegetables supply chain	Case
Catalá et al. (2016)	Apples and pears	Mixed integer linear programming	Multi-objective optimization	Optimization criteria in the lexicographic method	minimize the demand violation, maximize the economic benefit of the system	Optimize the model in the fruit industry supply chain	Case
Gholamian and Taghanzadeh (2017)	Wheat	Mixed integer linear programming	Single-objective optimization	Exact	Minimize the total cost	Integrated network design of wheat supply chain	Case
Cheraghalipour et al. (2018)	Citrus	Mixed integer linear programming	Bi-level optimization	Metaheuristics, Hybrid metaheuristics	Minimize the total cost	Location-allocation model to optimize the total costs	Case
Cheraghalipour et al. (2019)	Rice	Nonlinear programming	Bi-level optimization	Metaheuristics	Minimize the total cost	Designing and solving a bi-level model for rice supply chain	Case

Table 3. Continued

Roghanian and Cheraghalipour (2019)	Citrus	Multi-objective optimization	Multi-objective optimization	ε-constraint, Metaheuristics	Minimize the total cost and minimize CO2 emissions	Optimizing a closed-loop citrus supply chain	Case
Liao et al. (2020)	Citrus	Mixed integer linear programming	Multi-objective optimization	Hybrid metaheuristics	Minimize the total cost	CLSC network design for walnut industry	Case
Salehi-Amiri et al. (2021)	Walnut	Mixed integer linear programming	Multi-objective optimization	Exact, metaheuristics, Hybrid Metaheuristics	Minimize the total cost	CLSC network design for walnut industry	Case
Chouhan et al. (2021)	Sugarcane	Mixed integer linear programming	Multi-objective optimization	Metaheuristic, Hybrid metaheuristics	Minimize the total cost	Designing a multi-echelon sugarcane closed-loop supply chain network	Case
Salehi-Amiri et al. (2022)	Avocado	Linear programming	Multi-objective optimization (two objectives)	GAMS software and its CPLEX	Minimize the total cost and job employment, Maximize opened locations	CLSC network for the avocado industry	Case
This study	Pomegranate	Mixed integer linear programming	Multi-objective optimization (three objectives)	Augmented ε-constraint method, Metaheuristics, Hybrid metaheuristics	Minimize the total cost, Minimize the supply risk and maximize responsiveness to customers demand	Designing a CLSC network and a solving model for agriculture supply chain	Case

3- Problem definition

This paper proposes a design for a closed-loop chain of supplying pomegranates. The corresponding logistics network is designed for several periods and covers manufacturers, distribution centers, customers, factories, reprocessing centers (compost centers), and compost customers (compost markets). As shown in figure 3, goods are transported from the manufacturer to the customers, distribution centers and factories in a forward flow. The designed network of fruits in the forward flow exists in only three periods because the maximum duration of mass production periods is three months. In this flow, the customers also receive their goods from the distribution centers, and the demands are met by the manufacturer. The distribution centers can ship goods in eight periods, as the maximum time for product storage. The fruit demand period is eight months too. Besides, the customer locations are considered fixed.

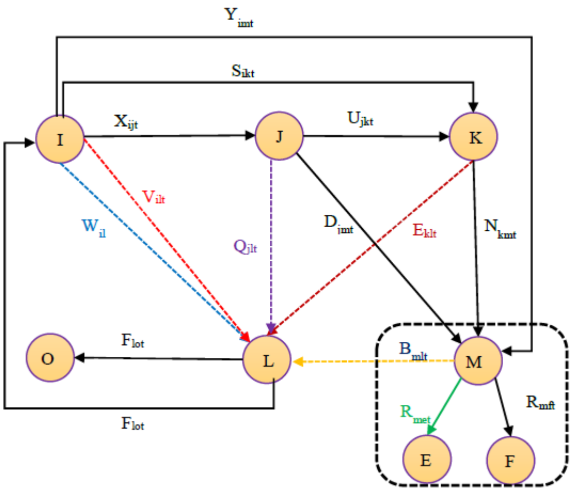

Fig1. Flowchart of the proposed CLSC

The factories in the supply chain obtain the fruit that they need from the producers and the distribution centers in the forward part of the chain. A factory consists of a food and pharmaceutical sector that serves to prepare the products and send them to the market. Another feature of this chain is the processing of pomegranate wastes, such as seperating the peel from the other parts for conversion and reprocessing. As figure 2 shows, bioethanol can be extracted from pomegranate peel and the other components of the fruit waste (Amorim et al. 2012). One of the applications of this extract is in car fuel production (Pourghader Chobar et al. 2021) and (Bayanati et al. 2022).

Rotten fruits on trees transmit their pests to other fruits. To prevent the spread of pests to the whole garden, the spoiled fruit is identified by image processing and artificial intelligence and carried out of the garden to compost centers. The returned fruit is sent to vermicompost centers, converted into organic fertilizers, and transferred to compost customers in the reverse flow. Since the producers (orchards) can be the customers of fertilizers as well, the network is considered as a supply chain of cyclic packages where the producers are the same as the compost customers (figure 3).

Millions of tons of biowaste are dumped or incinerated every year, which causes many environmental problems and imposes enormous costs of transporting, disposing and incinerating. A major method of processing organic wastes is recycling them to vermicompost. This helps to maintain the environment and the public health while producing a significant amount of beneficial organic fertilizer called vermicompost. It is an organic biofertilizer obtained through the rapid and stable extraction of organic matter from the gastrointestinal tract of a particular earthworm (Nematollahi and Tajbakhsh, 2020) and (Ahumada and Villalobos, 2009) and (Shukla and Jharkharia, 2013).

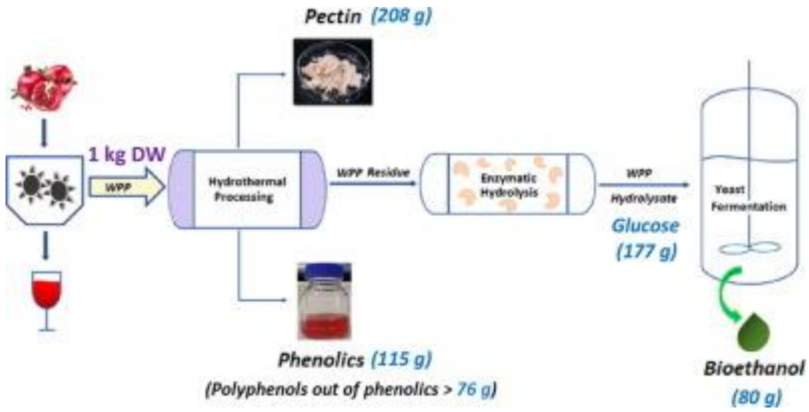

Fig 2. Process of extracting bioethanol from pomegranate wastes

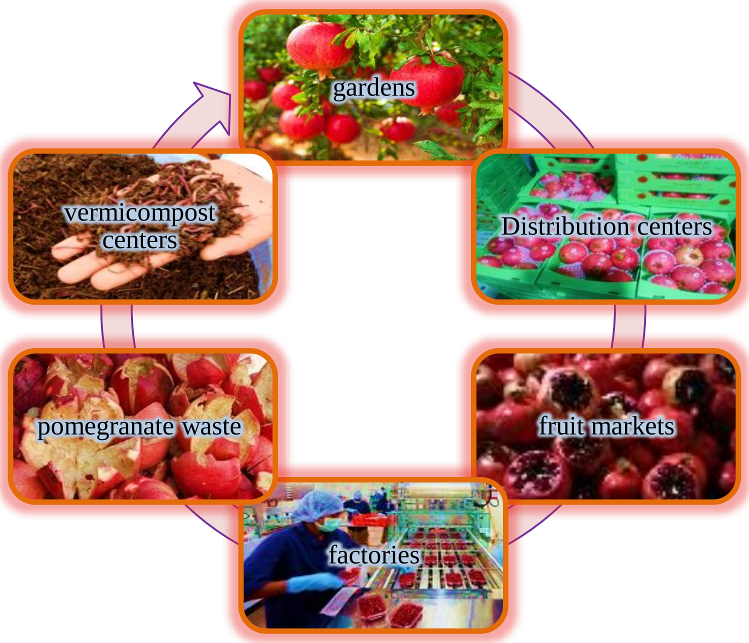

Fig 3. Flow of the returned pomegranate and its conversion to vermicompost

4- Problem modelling

This section introduces the indices, parameters and decision variables of the problem and then describes the proposed multi-objective mathematical model. The model is developed according to the definition of the problem and takes into account certain assumptions. Its objectives are to minimize the supply chain costs (i.e., costs of transportation, construction of potential locations for distribution centers, inventory maintenance, production in gardens, and processing), to minimize the risks involved and to maximize the demand response.

Indicators:

$i = 1,2, \ldots, I$ Production sites (gardens)
$j = 1,2, \ldots, J$ Distribution centers
$k = 1,2, \ldots, K$ Customer places (fruit markets)
$m = 1,2, \ldots, M$ Factory locations
$f = 1,2, \ldots, F$ Agro-food market places
$e = 1,2, \ldots, E$ Ethanol market places
$l = 1,2, \ldots, L$ Composting sites
$o = 1,2, \ldots, O$ Compost customer sites
$p = 1,2, \ldots, P$ Crop (fruit) production
$t = 1,2, \ldots t', \ldots, T$ Time periods

Parameters:

$\tilde{f}_j$ Fixed costs of establishing distribution center "*j*"

$\tilde{f}_l$ Fixed costs of establishing recycling center *l*

$\tilde{f}_m$ Fixed costs of establishing factory *m*

$\tilde{C}x_{ij}$ Shipping cost per production unit from producer "*i*" to distributor *j*

$\tilde{C}s_{ik}$ Shipping cost per production unit from producer "*i*" to cutomer *k*

$\tilde{C}y_{im}$Sshipping cost per production unit from producer "*i*" to factory *m*

$\tilde{C}v_{il}$ Shipping cost per production unit (after harvest) from producer "*i*" to recycling center *l*

$\tilde{C}w_{il}$Shipping cost per production unit (before harvest/pest control) from producer "*i*" to recycling center *l*

$\tilde{C}u_{jk}$ Shipping cost per production unit from distributor "*j*" to cutomer *k*

$\tilde{C}d_{jm}$ Shipping cost per production unit from distributor "*j*" to factory *m*

$\tilde{C}q_{jl}$ Shipping cost per production unit from distributor "*j*" to recycling center *l*

$\tilde{C}e_{kl}$ Shipping cost per production unit from customer "*k*" to recycling center *l*

$\tilde{C}n_{km}$ Shipping cost per production unit from customer "*k*" to factory *m*

$\tilde{C}b_{ml}$ Shipping cost per production unit from factory "*m*" to recycling center *l*

$\tilde{C}f_{lo}$ Shipping cost per production unit from composting center "*l*" to compost market *o*

$\tilde{C}r_{mf}$ Shipping cost per production unit from factory "*m*" to agro-food factory's market *f*

$\tilde{C}r_{me}$ Shipping cost per production unit from factory "*m*" to agro-food factory's market *e*

$\tilde{C}h_t$ Product storage cost by the distribution center in period *t*

$\tilde{C}a_t$ Cost of pesticides at the production site (gardens) identified through artificial intelligence in period *t*

$\tilde{C}p_t$ Cost of product processing and packaging by the distribution center in period *t*

$\tilde{C}r_t$ Cost of compost production by the recycling center in period *t*

$\tilde{C}_{mft}$ Cost of producing food and pharmaceuticals by the corresponding factories in period *t*

$\tilde{C}_{met}$ Cost of producing ethanol products by the corresponding factory in period *t*

$\tilde{C}p'$ Cost of production by the gardens

$\widetilde{RC}_{pit}$ Cost of reducing the production risk of product *p* from supplier *i* in period *t*

$\widetilde{SR}_{pit}$ Risk of supplying product *p* from supplier *i* in period *t*

$\widetilde{MSR}_{pt}$ Maximum supply risk allowed to produce product *p* in period *t*

$\widetilde{MP}_{pit}$ Maximum product *p* from garden *i* in period *t*

$\widetilde{RV}_{it}$ Disruption or natural disasters period from the supplier *i* in period *t*

$\widetilde{R\varphi}_{pt}$ Severity of disruption or natural disasters for crop *p* in period *t*

$\widetilde{R\theta}_{pit}$ Frequency rate of the crop failure or the natural disasters of product *p* from supplier *i* in period *t*

$\tilde{d}_{kt}$ Demand of customer *k* (fruit market) in period *t*

$\tilde{d}'_{ot}$ Demand for the product produced through recycling (composting) by compost customer *o* in period *t*

$\tilde{d}''_{ft}$ Demand for factory-produced products (food and pharmaceuticals) by customer *f* in period *t*

$\tilde{d}'''_{et}$ Demand for factory-produced product (ethanol) by customer *e* in period *t*

$\widetilde{\lambda c}_{it}$ Maximum production capacity *i* in period *t*

$\widetilde{\lambda h}_{jt}$ Maintenance capacity of distributor *j* in period *t*

$\widetilde{\lambda r}_{lt}$ Production and storage capacity of recycling center *l* in period *t*

$\widetilde{\lambda p}_{mft}$ Factory capacity for the production and storage of food and pharmaceuticals in period *t*

$\widetilde{\lambda p}_{met}$ Production and storage capacity of the ethanol plant in period *t*

$\tilde{\alpha}_t$ Percentage of the product waste harvested by the manufacturer in period *t*

$\tilde{\alpha}'_t$ Percentage of crop waste before harvest (pest control) by the producer in period *t*

$\tilde{\beta}_t$ Percentage of the product waste stored by the distribution center in period *t*

$\tilde{\beta}'_t$ Percentage of the semi-rotted crop waste stored by the distribution center in period *t*

$\tilde{\theta}_t$ Percentage of the product waste stored by the customer in period *t*

$\tilde{\theta}'_t$ Percentage of the semi-rotten products stored by the customer in period *t*

$\tilde{\gamma}_t$ Percentage of the product waste after production by the factory in period *t*
ρ Weight factor (importance) of the response to forward currents
$1-\rho$ Weight factor (importance) of the response to backward flows
$\underset{\sim}{\omega}$ Coefficient of product conversion into processed crop in the factory
$\underset{\sim}{\varphi}$ Coefficient of waste products conversion into processed products in the recycling center
M' A large positive value
Decision variables:
X_{ijt} The products transferred from manufacturer *i* to distributor *j* in period *t*
Y_{imt} The products shipped from manufacturer *i* to factory *m* in period *t*
S_{ikt} The products sent from manufacturer *i* to customer *k* in period *t*
V_{ilt} The returned (rotten) products sent from manufacturer *i* to recycling center *l* in period *t*
W_{ilt} The products (rotten before harvest) sent from producer *i* to recycling center *l* in period *t*
U_{jkt} The product shipped from distributor *j* to customer *k* in period *t*
Q_{jlt} Returned (semi rotten) product sent from distributor *j* to recycling center *l* in period *t*
D_{jmt} The (semi-rotten) product transferred from distributor *j* to factory *m* in period *t*
E_{klt} The returned (rotten) product sent from customer *k* to recycling center *l* in period *t*
N_{kmt} The returned (semi-rotten) product sent from customer *k* to factory *m* in period *t*
B_{mlt} The returned (waste) product sent from factory *m* to recycling center *l* in period *t*
F_{lot} The composts produced and sent from recycling center *l* to compost market *o* in period *t*
R_{mft} The products produced and shipped from factory *f* to factory market *e* in period *t*
R_{met} The products produced and shipped from factory *m* to factory market *e* in period *t*
Ih_{jt} The products stored in distribution center *j* over period *t*
λ_{it} Crop production by producer "*i*" in period "*t*"
$\vartheta_j \begin{cases}0\\1\end{cases}$ If the distribution center is established in candidate location *j*, a numeric value of one is adopted; otherwise, a value of zero will be assigned.
$\eta_l \begin{cases}0\\1\end{cases}$ If the recycling center is established in a candidate place, a value of one is assigned; otherwise, a value of zero will be allotted.
$\zeta_m \begin{cases}0\\1\end{cases}$ If the factory is established in candidate location *m*, a value of one holds; otherwise, a value of zero should be assigned.
$\sigma_{pi} \begin{cases}0\\1\end{cases}$ If product *p* is generated from supplier *i*, assign a value of one; otherwise, consider a value of zero.

Objective functions:

$$\min z = z_1 + z_2 + z_3 + z_4 + z_5 \tag{1}$$

$$z_1 = \sum_{j=1}^{J} \widetilde{f_J} \times \vartheta_j + \sum_{l=1}^{L} \widetilde{f_l} \times \eta_l + \sum_{m=1}^{M} \tilde{f}_m \times \zeta_m + \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T} \widetilde{SR}_{pit} \times \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T} \widetilde{RC}_{pit} \times \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T} \sigma_{pit} \tag{2}$$

$$z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{t'}\widetilde{Cx}_{ij} \times X_{ijt} + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{t'}\widetilde{Cs}_{ik} \times S_{ikt} + \sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{t=1}^{t'}\widetilde{Cy}_{im} \times Y_{imt}$$
$$+ \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{t'}\widetilde{Cv}_{il} \times V_{ilt} + \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{t'}\widetilde{Cw}_{il} \times W_{ilt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\widetilde{Cu}_{jk} \times U_{jkt}$$
$$+ \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T}\widetilde{Cq}_{jl} \times Q_{jlt} + \sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{t=1}^{T}\widetilde{Cd}_{jm} \times D_{jmt} + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T}\widetilde{Ce}_{kl} \times E_{klt}$$
$$+ \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{t=1}^{T}\widetilde{Cn}_{km} \times N_{kmt} + \sum_{m=1}^{M}\sum_{l=1}^{L}\sum_{t=1}^{T}\widetilde{Cb}_{ml} \times B_{mlt} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T}\widetilde{Cf}_{lo} \times F_{lot}$$
$$+ \sum_{m=1}^{M}\sum_{f=1}^{F}\sum_{t=1}^{T}\widetilde{Cr}_{mf} \times R_{mft} + \sum_{m=1}^{M}\sum_{e=1}^{E}\sum_{t=1}^{T}\widetilde{Cr}_{me} \times R_{met} \tag{3}$$

$$z_3 = \sum_{i=1}^{I}\sum_{t=1}^{t\prime}\lambda_{it} \times \widetilde{Ca}_t \tag{4}$$

$$z_4 = \sum_{j=1}^{J}\sum_{t=1}^{T} Ih_{jt} \times \widetilde{Ch}_t \tag{5}$$

$$z_5 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{t'} X_{ijt} \times \widetilde{Cp}_t + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} F_{lot} \times \widetilde{Cr}_t + \sum_{m=1}^{M}\sum_{f=1}^{F}\sum_{t=1}^{T} R_{mft} \times \widetilde{Cm}_t$$
$$+ \sum_{m=1}^{M}\sum_{e=1}^{E}\sum_{t=1}^{T} R_{met} \times \widetilde{Cm}_t + \sum_{i=1}^{I}\sum_{t=1}^{T}\lambda_{it} \times \widetilde{Cp}'_t \tag{6}$$

$$minzz = \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T}\widetilde{SR}_{pit} \times \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T}\widetilde{RC}_{pit} \times \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T}\sigma_{pit} + \sum_{i=1}^{I}\sum_{t=1}^{T}\widetilde{RV}_{it} \times \sum_{p=1}^{P}\sum_{t=1}^{T}\widetilde{R\varphi}_{pt}$$
$$\times \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T}\widetilde{R\theta}_{pit} \tag{7}$$

$$\max Z' = \rho \times (\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{t'} S_{ikt} + \sum_{j=1}^{j}\sum_{k=1}^{K}\sum_{t=1}^{T} U_{jkt})/(\sum_{k=1}^{K}\sum_{t=1}^{T}\tilde{d}_{kt}) + (1-\rho) \times (\sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} F_{lot}$$
$$+ \sum_{m=1}^{M}\sum_{f=1}^{F}\sum_{t=1}^{T} R_{mft} + \sum_{m=1}^{M}\sum_{e=1}^{E}\sum_{t=1}^{T} R_{met})/(\sum_{o=1}^{O}\sum_{t=1}^{T}\tilde{d}'_{ot} + \sum_{f=1}^{F}\sum_{t=1}^{T}\tilde{d}''_{ft}$$
$$+ \sum_{e=1}^{E}\sum_{t=1}^{T}\tilde{d}'''_{et}) \tag{8}$$

This model has three objective functions including cost minimization, risk reduction and accountability maximization. Equation (1) deals with the minimization of the costs. There are five types of cost presented in equations (2) to (6). Equation (2) addresses the fixed costs of establishing the distribution, recycling and manufacturing centers. It should be noted that distribution and recycling centers can be either actual or potential points. To make it possible, rather than the addition of an index, the cost of constructing actual points is assumed to be zero in the parameters. Equations (3) to (5) are respectively concerned with the following:

- transportation costs (comprising forward and backward costs)
- the cost of using artificial intelligence for pest control in gardens
- the cost of maintaining the processed products

Equation (6) regards operating costs, including the costs of energy, processing, packaging, reprocessing and food industries. Equation (7) defines the function of the second objective, which is to minimize the risk in the chain by considering the cost of reducing the risk of supplying the product. It is possible to determine the magnitude of the risk by multiplying the severity, frequency and probability of the chain disorders, as three indicators. Equation (8) defines the third objective function, namely the maximization of accountability. In this regard, the response is divided into two parts. The first pertains to the customers of the main product, and the second concerns the customers of the processed product as well as the food and energy conversion industries.

Constraints:

$$\lambda_{it} \times \left(1-(\alpha_t+\alpha'_t)\right) = \sum_{j=1}^{J} X_{ijt} + \sum_{k=1}^{K} S_{ikt} + \sum_{m=1}^{M} Y_{imt} \qquad \forall i \in I, \forall t \in t' \tag{9}$$

$$\sum_{i=1}^{I} \sum_{t=1}^{T=t'} X_{ijt} \le M' \times \vartheta_j \qquad \forall j \in J \tag{10}$$

$$\lambda_{it} \le \widetilde{\lambda c}_{it} \qquad \forall i \in I, \forall t \in t' \tag{11}$$

$$Ih_{j(t-1)} + \sum_{j=1}^{J} X_{ijt} = Ih_{jt} + \sum_{k=1}^{K} U_{jkt} + \sum_{l=1}^{L} Q_{jlt} + \sum_{m=1}^{M} D_{jmt} \qquad \forall i \in I, \forall t \in T \tag{12}$$

$$Ih_{jt} \le \widetilde{\lambda h}_j \qquad \forall j \in J, \forall t \in T \tag{13}$$

$$\sum_{j=1}^{j} U_{jkt} + \sum_{i=1}^{I} S_{ikt} \le \tilde{d}_{kt} \qquad \forall k \in K, \forall t \in T \tag{14}$$

$$\sum_{l=1}^{L} V_{ilt} \le \tilde{\alpha}_t \times \lambda_{it} \qquad \forall i \in I, \forall t \in t' \tag{15}$$

$$\sum_{t=1}^{t'} \sum_{i=1}^{I} V_{ilt} \le M' \times \eta_l \qquad \forall l \in L \tag{16}$$

$$\sum_{l=1}^{L} W_{ilt} \le \tilde{\alpha}'_t \times \lambda_{it} \qquad \forall i \in I, \forall t \in t' \tag{17}$$

$$\sum_{t=1}^{t'} \sum_{i=1}^{I} W_{ilt} \le M' \times \eta_l \qquad \forall l \in L \tag{18}$$

$$\sum_{l=1}^{L} Q_{jlt} \le \tilde{\beta}_t \times Ih_{j(t-1)} \qquad \forall j \in J, \forall t \in T \tag{19}$$

$$\sum_{t=1}^{T}\sum_{j=1}^{J} Q_{jlt} \leq M' \times \eta_l \qquad \forall l \in L \tag{20}$$

$$\sum_{l=1}^{L} E_{klt} \leq \tilde{\theta}_t \times d_{kt} \qquad \forall k \in K, \forall t \in T \tag{21}$$

$$\sum_{t=1}^{T}\sum_{k=1}^{K} E_{klt} \leq M' \times \eta_l \qquad \forall l \in L \tag{22}$$

$$\sum_{l=1}^{L} B_{mlt} \leq \tilde{\gamma}_t \times (\tilde{d}''_{ft} + \tilde{d}'''_{et}) \qquad \forall m \in M, \forall t \in T \tag{23}$$

$$\sum_{t=1}^{T}\sum_{m=1}^{M} B_{mlt} \leq M' \times \eta_l \qquad \forall l \in L \tag{24}$$

$$\sum_{m=1}^{M} D_{jmt} \leq \tilde{\beta}'_t \times Ih_{j(t-1)} \qquad \forall j \in J, \forall t \in T \tag{25}$$

$$\sum_{t=1}^{T}\sum_{j=1}^{J} D_{jmt} \leq M' \times \zeta_m \qquad \forall m \in M \tag{26}$$

$$\sum_{m=1}^{M} N_{kmt} \leq \tilde{\theta}'_t \times \tilde{d}_{kt} \qquad \forall k \in K, \forall t \in T \tag{27}$$

$$\sum_{t=1}^{T}\sum_{k=1}^{K} N_{kmt} \leq M' \times \zeta_m \qquad \forall m \in M \tag{28}$$

$$\sum_{m=1}^{M} Y_{imt} \leq \tilde{\alpha}_t \times \lambda_{it} \qquad \forall i \in I, \forall t \in T \tag{29}$$

$$\sum_{t=1}^{T}\sum_{i=1}^{I} Y_{imt} \leq M' \times \zeta_m \qquad \forall m \in M \tag{30}$$

$$(\sum_{i=1}^{I} Y_{imt} + \sum_{j=1}^{J} D_{jmt} + \sum_{k=1}^{K} N_{kmt}) \times \tilde{\omega} = \sum_{f=1}^{f} R_{mft} + \sum_{e=1}^{E} R_{met} \qquad \forall m \in M, \forall t \in T \tag{31}$$

$$\sum_{f=1}^{F} R_{mft} + \sum_{e=1}^{E} R_{met} \leq \widetilde{\lambda p}_{mf} + \widetilde{\lambda p}_{me} \qquad \forall m \in M, \forall t \in T \tag{32}$$

$$\sum_{m=1}^{M} R_{mft} \leq \tilde{d}"_{ft} \qquad \forall f \in F, \forall t \in T \tag{33}$$

$$\sum_{m=1}^{M} R_{met} \leq \tilde{d}'''_{et} \qquad \forall e \in E, \forall t \in T \tag{34}$$

$$\left(\sum_{i=1}^{I} V_{ilt} + \sum_{i=1}^{I} W_{ilt} + \sum_{j=1}^{J} Q_{jlt} + \sum_{m=1}^{M} B_{mlt} + \sum_{k=1}^{K} E_{klt}\right) \times \tilde{\varphi} = \sum_{o=1}^{O} F_{lot} \qquad \forall l \in L, \forall t \in T \tag{35}$$

$$\sum_{o=1}^{O} F_{lot} \leq \widetilde{\lambda r}_{l} \qquad \forall l \in L, \forall t \in T \tag{36}$$

$$\sum_{l=1}^{L} F_{lot} \leq \tilde{d}'_{ot} \qquad \forall o \in O, \forall t \in T \tag{37}$$

$$\sum_{p=1}^{P} SR_{pit} \times \sum_{p=1}^{P} \sigma_{pit} \leq \sum_{p=1}^{P} \widetilde{MSR}_{pt} \qquad \forall i \in I, \forall t \in T \tag{38}$$

$$\sum_{j=1}^{J} X_{ijt} + \sum_{k=1}^{K} S_{ikt} + \sum_{m=1}^{M} Y_{imt} + \sum_{i=1}^{I} V_{ilt} + \sum_{i=1}^{I} W_{ilt} \leq \sum_{p=1}^{P} \widetilde{MP}_{it} \qquad \forall j \in J, \forall k \in K, \ \forall m \in M, \forall l \in L, \forall t \in T \tag{39}$$

$$\vartheta_j, \eta_l, \zeta_m, \sigma_{pit} \in \{0,1\} \qquad \forall j \in J, \forall l \in L, \forall m \in M, \forall p \in P, \forall i \in I \tag{40}$$

$$X_{ijt}, S_{ikt}, Y_{imt}, V_{ilt}, W_{ilt}, U_{jkt}, D_{jmt}, Q_{jlt}, N_{kmt}, E_{klt}, R_{mft}, R_{met}, B_{mlt}, F_{lot} \geq 0 \qquad \forall i \in I, j \in J, k \in K, m \in M, l \in L, f \in F, e \in E, t \in T \tag{41}$$

$$Ih_{jt} \geq 0, \lambda_{it} \geq 0 \quad \forall i \in I, \forall j \in J, \forall t \in T \tag{42}$$

Each of the constraints delineated above plays a certain role in the mathematical model. Constraint (9) shows that the producers minus wastes equal the transfer from those producers to the distributors, target markets and factories. Constraint (10) is related to constraint (9) and emphasizes that shipments to potential distributors will occur if the site is established. Constraint (11) indicates that the amount of the product manufactured by smaller producers is equal to their maximum capacity. Constraint (12) states that the distributor’s inventory in each period equals the inventory in the previous period minus the waste of the previous period plus the new products entering the warehouse minus the products going out of the warehouse to the processing and packaging lines and factories. Constraint (13) states that the maximum inventory of distributors is smaller or equal to the warehouse capacity. Constraint (14) means that the market demand in each period is greater or equal to the products of the producers and distributors. Constraints (15) to (24) indicate that the amount of the waste in each section of the reverse flow is displayed if recycling centers are established. Constraints (25) to (30) denote that the inputs from such sectors as production, distribution, fruit markets and customers are sent to factories including manufacturers as well as food and energy industries. Constraint (31) signifies that the total input sent from the production and distribution centers, fruit markets and customers to the factory multiplied by the conversion rate of the processed products in the factory is equal to the total products sent to the market from food and energy production plants. Constraint (32) implies that the total output of factories sent to the customer or market is less than or equal to the production capacity of food and energy factories. Constraints (33) and (34) assume that all the products of a factory sent to a smaller factory or market are equal to the customer demand and the market capacity of the food and energy factory. Accordingly, constraint (33) is related to the capacity of food factories as well as their market demand and customers. Constraint (34), however, is about the capacity of energy factories as well as their market demand and customers. Constraint (35) shows that the total waste sent to recycling centers from producers, distributors, customers and factories multiplied by the rate of waste product conversion to compost is equal to the total recycled product sent to markets and compost customers. Constraint (36) states that all the compost sent to the compost market and smaller customers is equal to the production capacity of recycling centers. Constraint (37) marks that all the compost sent to the compost market and smaller customers is equal to the demand of the compost customers. Constraint (38) assumes that the risk of providing the product from the supplier is multiplied if it is less than or equal to the maximum risk allowed to produce the product. Constraint (39) states that the total output of the orchards that goes to the distribution centers, fruit markets, customers and compost factories is smaller than the maximum products of the orchards. Equations (40) to (42) represent the last constraints and include the symbols of free variables (zero and one for the variables) and their positivity.

5- Numerical problem design

The current study was done with the aim of designing a multi-level closed-loop network including producers, distributors, customers, compost centers, compost customers, factories, and their customers. The customers were the buyers of the food industry and energy production centers. Figure (4) shows the map of the cities and provinces with the most pomegranate gardens. Considering the production capacities of different regions of Iran, the country can be divided into specific regions to identify the number of distribution centers in each region and establish their relationship with the consumption centers. The distance and capacity of an area as well as the product quality and final prices there effectively determine the number of distribution centers and the ways of communication between them and consumption centers. As a result, it is of significance to define each area in terms of the number of the distribution centers required and the movement routes.

The first sub-problem was the case study of this research, with which the proposed model and methods were validated. The cities selected for each area in this sub-problem are shown in table (4). For validation, twelve issues were dealt with in different dimensions. The corresponding data are presented in table (5). In this part of the study, according to the nature of the model, the examples were divided into small, medium, and large subsections. For this purpose, three examples with small dimensions, five examples with medium dimensions, and four examples with large dimensions were randomly generated to evaluate the model with real design conditions and desired parameters. The parameters of the model for the first problem are presented in table (6).The values of these parameters were assumed to be as listed below:

$\Phi = 1.1$ $\quad M' = 10^{15}$ $\quad \rho = 0.6$ $\quad cp' = 180$

f_j = 0, 0, 114290, and 585714 $\quad f_l$ = 0, 0, 14285, and 398060 $\quad f_m$ = 0, 0, 15285, and 45745

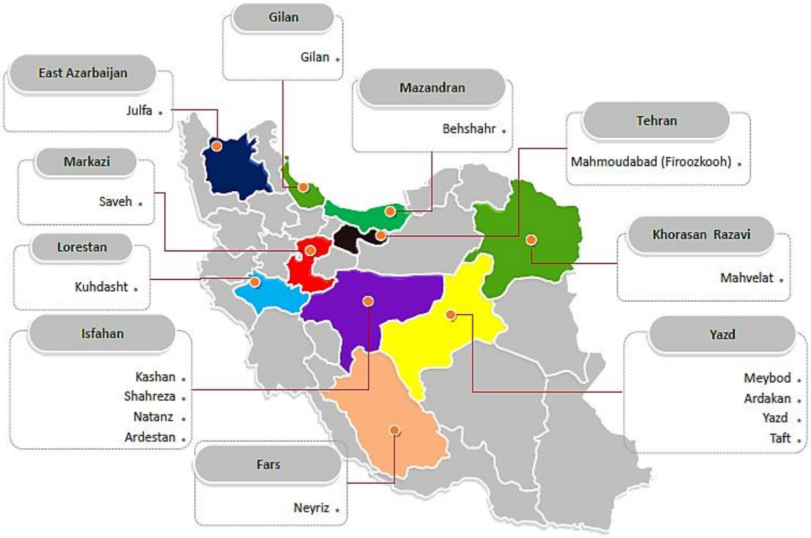

Fig 4. Map of Iran: the cities with the highest pomegranate production

Table 4. Cities selected for each index

Indicators	*i*	*J*	*K*	*L*	*O*	*m*	*f*	*e*	*P*
Cities	Saveh	Firoozkooh	Natanz	Gilan	Behshahr	Saveh	Ardestan	Ardakan	Behshahr
	Neyriz	Neyriz	Ardestan	Meybod	Neyriz	Gilan	Taft	Neyriz	Kashan
	Behshahr	Mehriz	Kuhdasht	Behshahr		Shahreza	Julfa		
		Mahvelat		Mahvelat		Ardakan			

Table 5. Dimensions of the problem

p	*o*	*l*	*e*	*f*	*M*	*k*	*j*	*i*	Problem number
4	2	4	2	3	4	3	4	3	1
4	2	4	3	4	4	4	5	3	2
5	3	5	4	5	5	6	5	4	3
5	4	5	4	6	5	8	6	4	4
6	5	6	5	6	6	10	6	5	5
8	5	6	5	7	6	10	7	5	6
10	6	6	6	8	7	11	7	6	7
12	7	7	6	8	7	11	7	7	8
14	7	8	7	9	8	12	9	7	9
16	8	8	7	9	8	12	9	8	10
18	8	9	8	10	9	13	10	8	11
20	9	9	8	10	9	13	10	9	12

Table 6. The values of the other model parameters

Parameter	Value	Unit
T	3	Period (months)
t'	3	Period (months)
Ω	1.12	percent
$1\text{-}\rho$	0.4	percent
λc_{it}	Uniform ~ [0, 95]	Ton
f_j	Uniform ~ [0, 585714]	Dollar
f_l	Uniform ~ [0, 398060]	Dollar
f_m	Uniform ~ [0, 42745]	Dollar
ch_t	Uniform ~ [58, 72]	Dollar/ton
cp_t	Uniform ~ [84, 104]	Dollar/ton
cr_t	[86, 137]	Dollar/ton
d_{kt}	Uniform ~ [1, 3]	Ton
λh_j	10 or 20 or 30	Ton
λp_{me}	Uniform ~ [4, 15]	Ton
λp_{mf}	Uniform ~ [4, 20]	Ton
λr_t	Uniform ~ [4, 10]	Ton
d'_{ot}	Uniform ~ [1, 3]	Ton
α_t	[0, 0.15]	percent
α'_t	[0, 0.8]	percent
β_t	[0, 0.05]	percent
β'_t	[0, 0.05]	percent
θ_t	[0.02, 0.05]	percent
θ'_t	[0.02, 0.049]	percent
γ_t	[0, 0.05]	percent
SR_{pit}	[0.02, 0.05]	percent
MSR_{pt}	[0.09]	percent
MP_{pit}	Uniform ~ [35, 119]	Ton/hectares
RC_{pit}	Uniform ~ [42, 73]	Dollar/ton
$RV_{i,t}$	uniform[1, 2]	range
$R\varphi_{p,t}$	0.003	Percent / intensity
$R\theta_{i,t}$	10	Abundance rate

6- Solution method

After the correctness of the model was proved, due to the model being hard, three meta-heuristic algorithms including NSGA-II, MOPSO, and HSA&TS were used to approach the real world and solve the examples in small, medium, and large dimensions. The algorithms were adjusted and analyzed according to the Taguchi method.

6-1- HSA&TS hybrid evolutionary algorithm

In the present study, a combination of the simulated multi-objective refrigeration algorithm and the multi-objective tabu search algorithm served to optimize the closed-loop supply chain problem. The implementation steps of the proposed hybrid algorithm are presented as follows:

1) First, the initial temperature (T_0) is set, an initial solution (x_0) is made as the current solution, and it is evaluated (F_0).
2) A new solution is made in the neighborhood of the current solution using the combined neighborhood solution generation operators such that the new responses cannot be defeated by the current response and does not be on the taboo list. In this case, it is evaluated($x_n \rightarrow x_{n+1}$).
3) The response to the new neighborhood (x_{n+1}) is accepted with the probability (p) of $\exp(\frac{-\Delta G}{T_k})$. If the new response ($x_{n+1}$) is accepted, the population archive is updated with the storage strategy.

4) The back-to-basics strategy is implemented, and a member of the archive population is randomly selected as the current response.
5) The temperature is reduced based on the temperature function ($\alpha < 1,\ T_{k+1} = \alpha T_k$).
6) If the termination conditions are met, the responses in the archive population are presented as the final optimal ones; otherwise, there is a return to Step 2.

6-2- Parameter setting

According to the Taguchi method, at first, certain levels (herein, three levels) are obtained for the parameters based on different runs and previous articles. The best parameter is selected based on MID and Time indices according to the design of the experiments and the relevant statistics. This task is performed through calculations for each algorithm in the following manner.

6-2-1- Parameter setting of the NSGA-II algorithm

First, the three primary levels of parameters are determined based on different runs and desired indices.

Table 7. Determination of the parameter levels of the NSGA-II algorithm

Parameters algorithm	Level 1	Level 2	Level 3
MaxIt	100	130	160
nPop	30	50	70
Probabilty of croosover	0.85	0.9	0.95
Probabilty of mutation	0.12	0.15	0.2

According to the random experiments by the Taguchi method, time response variables and MID index, the graphs of signal-to-noise statistics were obtained as follows:

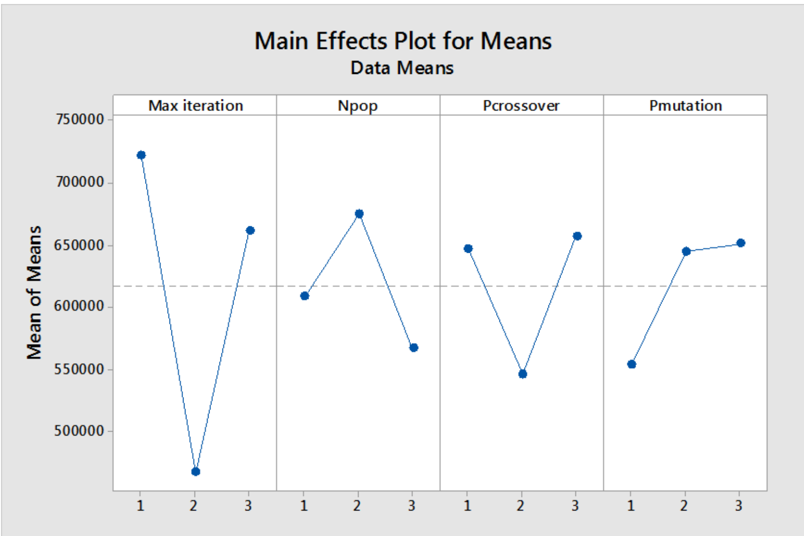

Fig 5. Average response variable index of the NSGA-II algorithm

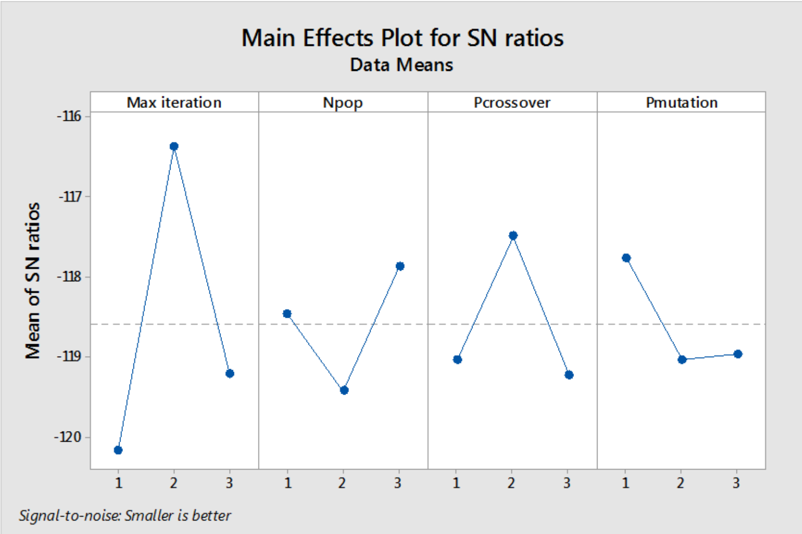

Fig 6. Average signal-to-noise ratio of the NSGA-II algorithm

According to the output of the above graph, the lowest level in the first graph must be determined for each parameter, while the same point on the average signal ratio graph cannot be accepted unless it is at the highest level. This is accounted for by the following table.

Table 8. Final parameters of the NSGA-II algorithm

Parameters algorithm	Value
MaxIt	130
nPop	50
Probabilty of croosover	0.9
Probabilty of mutation	0.12

6-2-2- Parameter setting of the MOPSO algorithm

The same process is repeated for the MOPSO algorithm.

Table 9. Determination of the parameter levels for the MOPSO algorithm

Parameters algorithm	Level 1	Level 2	Level 3
Max iteration	110	140	160
Npop	40	50	65
Repository Size	8	10	12
Inertia Weight	0.1	0.15	0.2
Inertia Weight Damping Rate	0.8	0.85	0.9
Number of Grids per Dimension	4	8	10
Leader Selection Pressure	1	2	3
Deletion Selection Pressure	2	3	4
Personal Learning Coefficient	1	2	3
Global Learning Coefficient	6	8	9
Inflation Rate	0.1	0.12	0.18

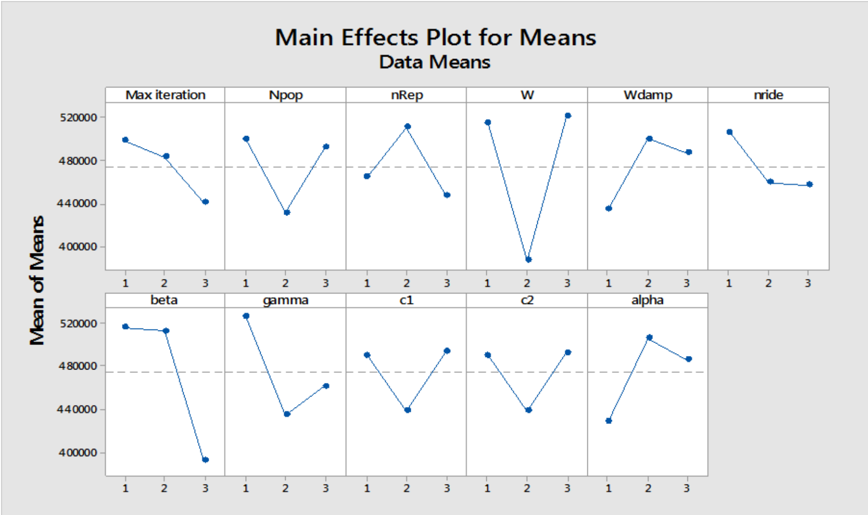

Fig 7. Average response variable index of the MOPSO algorithm

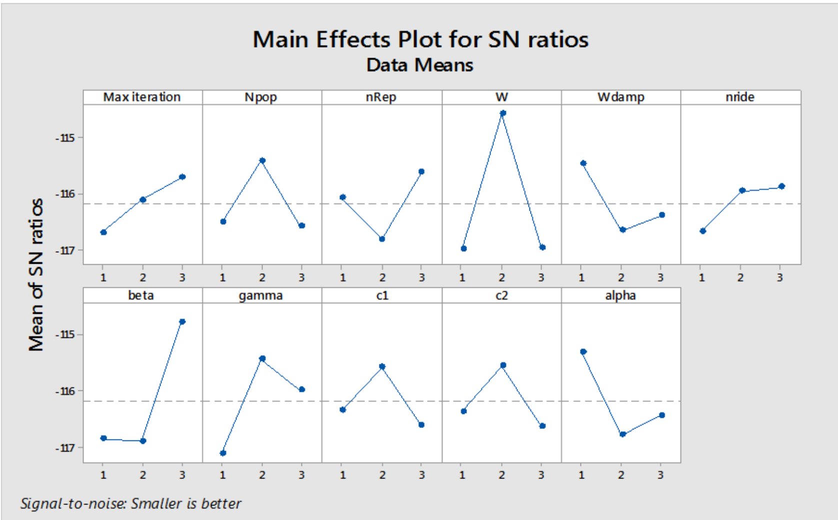

Fig 8. Average signal-to-noise ratio of the MOPSO algorithm

Finally, the corresponding parameters emerged as follows:

Table 10. Final parameters of the MOPSO algorithm

Parameters algorithm	Value
Max iteration	160
Npop	50
Repository Size	12
Inertia Weight	0.15
Inertia Weight Damping Rate	0.8
Number of Grids per Dimension	10
Leader Selection Pressure	3
Deletion Selection Pressure	3

6-2-3- Parameter setting of the HSA&TS algorithm

The same process is repeated for the HSA&TS algorithm.

Table 11. Parameter levels of the HSA&TS algorithm

Parameters algorithm	Level 1	Level 2	Level 3
MaxIt1	80	90	110
MaxIt2	30	40	50
T0	150	170	200
Alpha	0.8	0.93	0.97
Size of Tabu list	5	10	15

According to the random experiments by the Taguchi method, time response variables and MID index, the graphs of signal-to-noise statistics were obtained as follows:

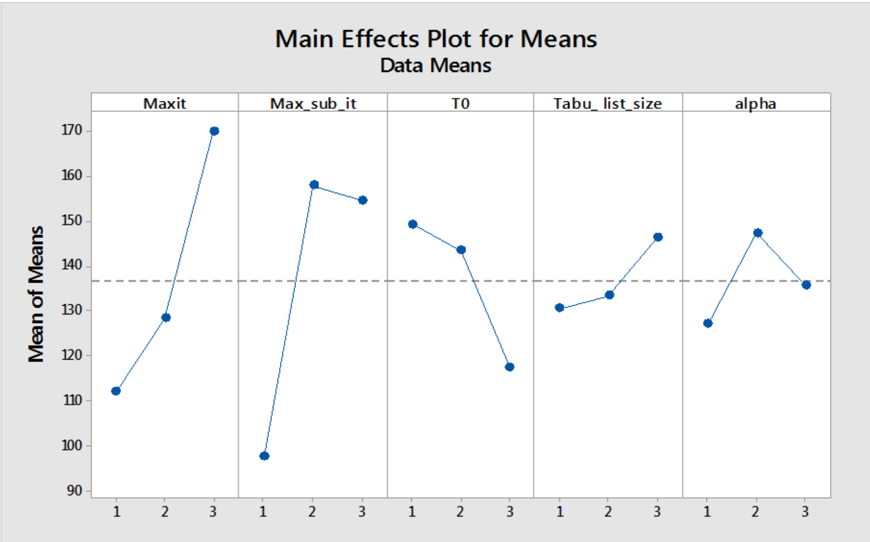

Fig 9. Average response variable index of the HSA&TS algorithm

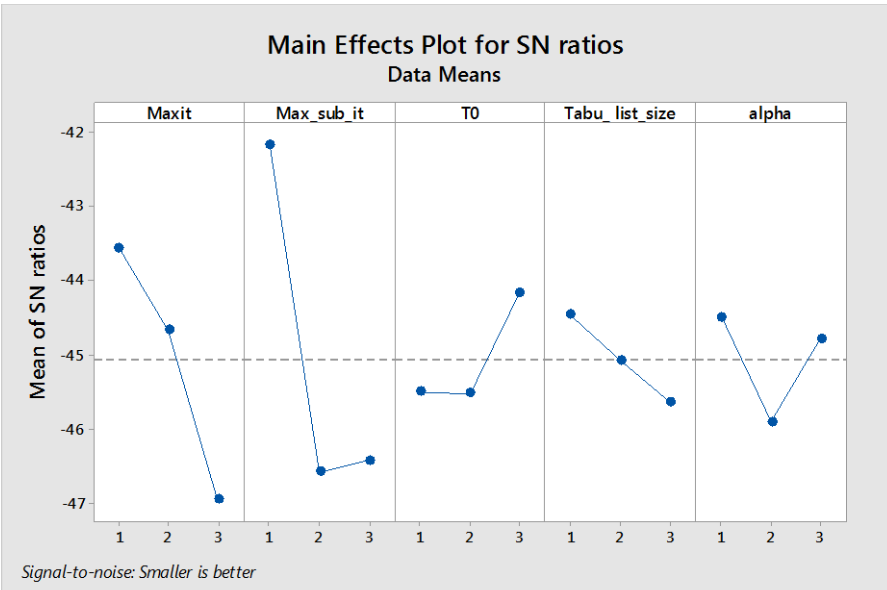

Fig 10. Average signal-to-noise ratio of the HSA&TS algorithm

Finally, the corresponding parameters are as follows:

Table 12. Final parameters of the HSA&TS algorithm

Parameters algorithm	Value
MaxIt1	80
MaxIt2	30
T0	200
Alpha	0.8
Size of Tabu list	10

7- Analysis of outputs

In this section, three examples are solved, and then Pareto front diagrams and their MID, Time, DM, NPS and SNS indices are compared to validate the continuation of solving with meta-heuristic algorithms. Also, F1, F2, and F3 represent the first, second and third objective functions, respectively.

Table 13. Output of the first example solved by the GAMS software

Row	F1	F2	F3
1	309511.7	43.06129	32.83574
2	312241.2	43.15746	34.10943
3	294004	44.01178	31.0994
4	299918.2	44.22673	32.70041
5	295312.4	43.2834	31.66422
6	301234.6	43.50951	30.93291
7	295923.1	44.00481	31.89589
8	300151.4	43.22392	29.38069
9	293805.4	43.9336	30.32375
10	296804.4	43.14727	32.35449

Table 14. Output of the first example solved by the HSA&TS algorithm

Row	F1	F2	F3
1	392418.8	55.358	27.1482
2	394106.9	55.358	28.2311
3	395905.7	55.358	26.83671
4	380662.8	55.358	24.32401
5	381699.6	55.358	25.82804
6	387765.1	55.358	26.72966
7	383097	55.358	25.99248
8	378415.1	56.33526	24.11476
9	381204.6	55.82489	25.16559
10	381510.3	56.33526	25.99764
11	388490	56.33526	27.16726
12	379346.7	55.358	24.09963
13	381110.3	56.33526	24.8138
14	385178.4	55.358	26.69739

Table 15. Output of the first example solved by the NSGA-II algorithm

Row	F1	F2	F3
1	381622.6	55.358	24.84056
2	379364.2	55.358	23.31604
3	380131	55.358	23.68423
4	381631.9	55.358	25.63412
5	383993.6	55.358	25.78019
6	395408.7	55.358	27.92903
7	385934.4	55.358	27.24566
8	380397.8	55.358	24.21721
9	384668.5	55.358	26.20516
10	384578.6	55.358	25.79996
11	423765.3	55.358	27.82078
12	384952.5	55.358	26.32911

Table 16. Output of the first example solved by the MOPSO algorithm

Row	F1	F2	F3
1	397651.6	55.358	25.41025
2	391115.7	55.82489	26.55117
3	394498.3	55.358	24.44385
4	388838.5	55.358	24.61918
5	389230.1	55.358	25.55065
6	389753.8	55.82489	21.66241

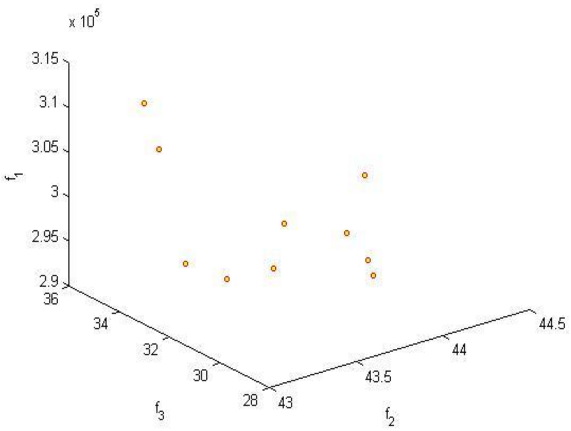

Fig 11. Pareto front of the Gams algorithm in the first example

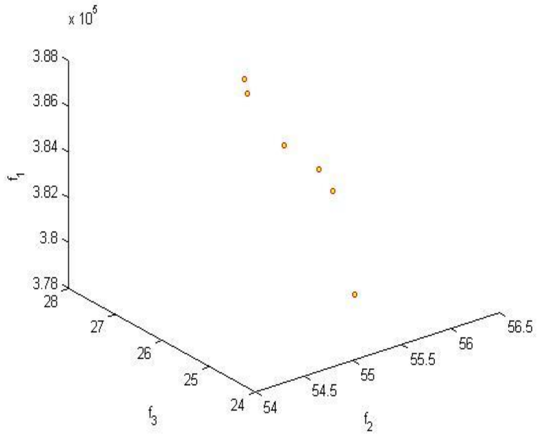

Fig 12. Pareto front of the MOPSO algorithm in the first example

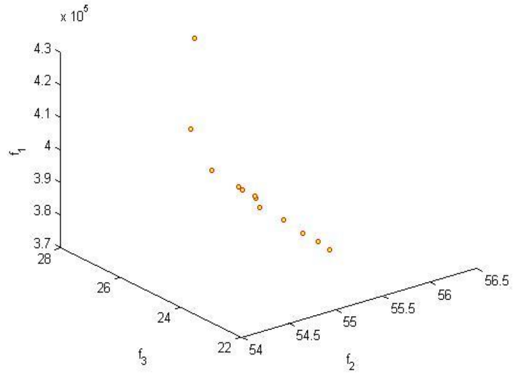

Fig 13. Pareto front of the NSGA-II algorithm in the first example

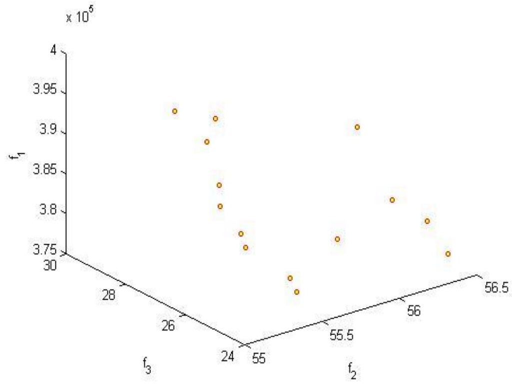

Fig 14. Pareto front of the HSA&TS algorithm in the first example

According to the Pareto front points produced in GAMS, which are the main criterion for the comparison of such fronts, the Pareto fronts produced in other algorithms were intuitively able to approach those of GAMS. To examine this issue in more detail, it is discussed in the next section according to the indices.

7-1-Performance evaluation indices

A method of dealing with the Pareto front issue is the use of performance evaluation indices, including MID, Time, DM, NPS, and SNS as standard indices.

7-1-1- MID index

The distance between the non-dominant solutions and the ideal point is calculated with this index. The smaller the value of this index, the higher the priority of the algorithm.

$$MID = \frac{\sum_{i \in n} \sqrt{\sum_{j=1}^{3} \left(\frac{f_{ji} - f_{jbest}}{f_{jbest} - f_{jworst}} \right)^2}}{n} \tag{43}$$

Table 17. Results based on the MID index

Problem Number	MID			
	Gams	NSGA-II	MOPSO	HSA&TS
1	0.0829	0.0983	0.1001	0.098
2	0.113	0.1632	0.2534	0.1602
3	0.3048	0.4927	0.506	0.3648
4	-	0.7651	0.672	0.6543
5	-	0.8475	0.8822	0.7557
6	-	0.9209	0.9806	0.8943
7	-	0.9375	0.9638	0.8373
8	-	0.8993	0.9774	0.8919
9	-	0.9701	0.9884	0.9047
10	-	0.9796	0.9875	0.9604
11	-	0.9988	0.9973	0.9682
12	-	0.9968	0.998	0.987

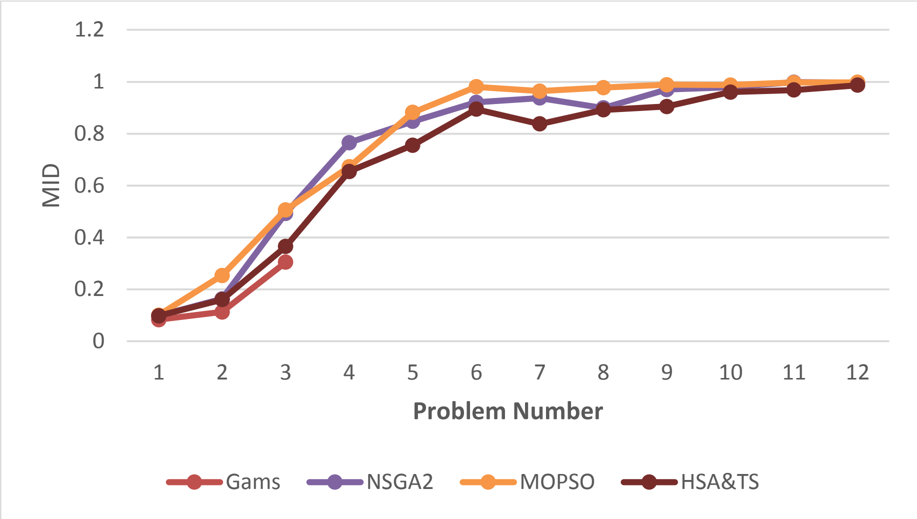

Fig 15. Results based on the MID index

According to figure (15), the GAMS output is the best in small dimensions. Despite the proximity of the GAMS solutions to the algorithm in the initial examples, the continuation of the meta-heuristic solution is reliable. However, in general, HAS&TS outperforms the other algorithms. This outperformance is examined with an analysis of variance (ANOVA) test. The test result with a significant level of 0.05 is presented in table 18.

Table 18. One-way analysis of variance

index	α	P-value	$\mu^{MID}_{\text{HAS\&TS}}$	μ^{MID}_{NSGA2}	μ^{MID}_{MOPSO}
MID	0.05	0.0467	0.7064	0.7558	0.7756

The equality assumption of the average communities of algorithms is presented as follows:

$$\begin{cases} H_0 : \mu^{MID}_{\text{HAS\&TS}} = \mu^{MID}_{MOPSO} = \mu^{MID}_{NSGA2} \\ H_1 : \mu^{MID}_{\text{HAS\&TS}} \neq \mu^{MID}_{MOPSO} \neq \mu^{MID}_{NSGA2} \end{cases} \tag{44}$$

Since the p-value is less than 0.05, the assumption of equality in terms of the MID random variable cannot be accepted. According to the results, the average MID is as follows, which shows the better performance of the HAS&TS algorithm.

$$\mu^{MID}_{\text{HAS\&TS}} < \mu^{MID}_{NSGA2} \leq \mu^{MID}_{MOPSO} \tag{45}$$

7-1-2- SNS index

The SNS index, also known as the extent index, is used to calculate the variety of Pareto solutions. The higher the value of this index, the higher the priority of the algorithm.

$$SNS = \sqrt{\frac{\sum_{i=1}^{n}\left(MID - C_i\right)^2}{n-1}}$$
$$C_i = \sum_{j=1}^{3}\left(\frac{f_{ji} - f_{jbest}}{f_{jbest} - f_{jworst}}\right)^2 \qquad \text{(46 and 47)}$$

Table 19. Results based on the SNS index

Problem Number	SNS			
	Gams	NSGA-II	MOPSO	HSA&TS
1	0.0442	0.0438	0.0368	0.0364
2	0.0491	0.0473	0.014	0.0143
3	0.291	0.0141	0.0076	0.2344
4	-	0.283	0.0273	0.3395
5	-	0.0629	0.0337	0.1575
6	-	0.0452	0.0012	0.1174
7	-	0.0061	0.0031	0.1256
8	-	0.1003	0.000875	0.0658
9	-	0.0038	0.000725	0.0686
10	-	0.004	0.0038	0.0226
11	-	0.0075	6.55E-05	0.0176
12	-	3.40E-03	0.000167	0.0119

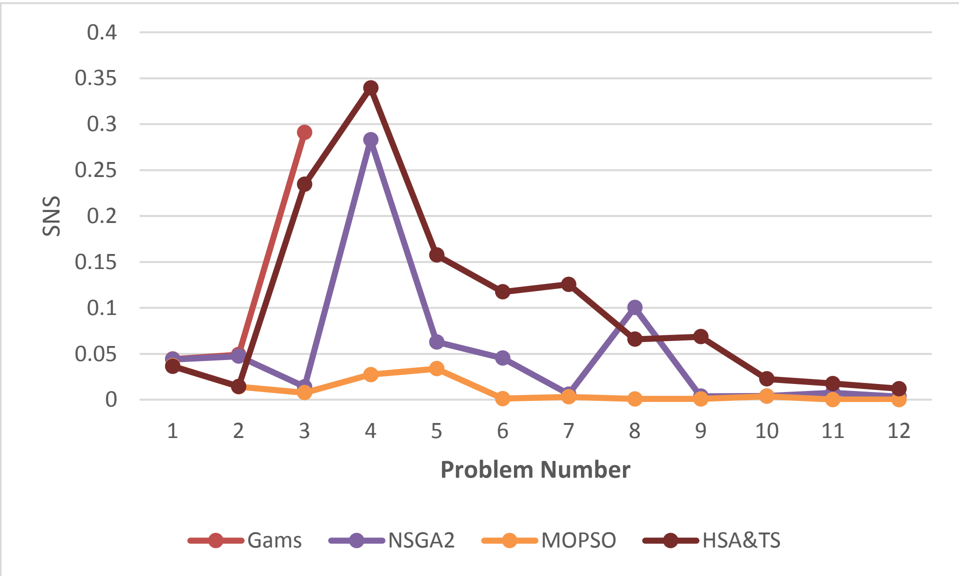

Fig 16. Results based on the SNS index

According to figure (16), compared to the algorithms in general, HAS&TS outperforms the other algorithms. An ANOVA test was used for a more detailed investigation. The equality assumption of the average communities of algorithms is presented as follows:

$$\begin{cases} H_0 : \mu^{\mathrm{SNS}}_{\mathrm{HAS\&TS}} = \mu^{\mathrm{SNS}}_{MOPSO} = \mu^{\mathrm{SNS}}_{NSGA2} \\ H_1 : \mu^{\mathrm{SNS}}_{\mathrm{HAS\&TS}} \neq \mu^{\mathrm{SNS}}_{MOPSO} \neq \mu^{\mathrm{SNS}}_{NSGA2} \end{cases} \tag{48}$$

The ANOVA output with a significant level of 0.05 is also as follows:

Table 20. One-way analysis of variance

index	α	P-value	$\mu^{SNS}_{\mathrm{HAS\&TS}}$	μ^{SNS}_{MOPSO}	μ^{SNS}_{NSGA2}
SNS	0.05	0.013	0.1010	0.0107	0.0518

Since the p-value is less than 0.05, the assumption of equality in terms of the SNS random variable cannot be accepted. According to the above results, the average SNS is as follows, which shows the better performance of the HAS&TS algorithm based on the SNS index.

$$\mu^{\mathrm{SNS}}_{\mathrm{HAS\&TS}} > \mu^{\mathrm{SNS}}_{NSGA2} > \mu^{\mathrm{SNS}}_{MOPSO} \tag{49}$$

7-1-3- DM index

This index calculates the extent of the solutions of the optimal Pareto front resulting from the algorithm. The higher the value of this index, the higher the priority of the algorithm.

$$DM = \sqrt{\sum_{i=1}^{3} \left(f_{i\max} - f_{imin} \right)^2} \tag{50}$$

Table 21. Results based on the DM index

Problem Number	**DM**			
	Gams	**NSGA-II**	**MOPSO**	**HSA&TS**
1	1.88E+04	1.44E+05	1.07E+04	1.75E+04
2	1.18E+05	1.12E+05	1.06E+06	1.17E+05
3	1.40E+06	1.26E+06	1.76E+05	1.37E+06
4	-	3242800	402810	5.37E+06
5	-	3.65E+06	1.72E+06	5.52E+06
6	-	4.74E+07	3.63E+06	8.38E+06
7	-	1.71E+08	4.09E+06	5.44E+07
8	-	1.25E+07	3.34E+06	1.09E+07
9	-	2.91E+08	2.30E+07	1.07E+08
10	-	6.04E+08	3.47E+07	4.66E+07
11	-	5.88E+09	9.94E+07	1.28E+08
12	-_	2.71E+09	1.66E+08	4.75E+07

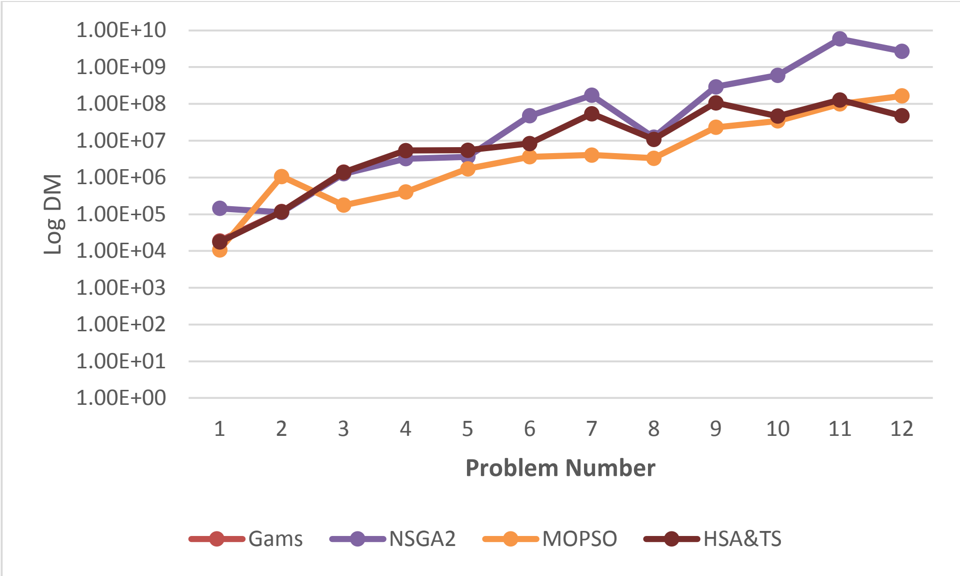

Fig 17. Results based on the DM index

According to figure (17), NSGA-II indicates a better performance than the other algorithms. An ANOVA test was used for a deeper investigation. The equality assumption of the average communities of algorithms is presented as follows:

$$\begin{cases} H_0 : \mu_{\text{HAS\&TS}}^{DM} = \mu_{MOPSO}^{DM} = \mu_{NSGA2}^{DM} \\ H_1 : \mu_{\text{HAS\&TS}}^{DM} \neq \mu_{MOPSO}^{DM} \neq \mu_{NSGA2}^{DM} \end{cases} \tag{51}$$

The ANOVA output with a significant level of 0.05 is also presented in the following table:

Table 22. One-way analysis of variance

index	α	P-value	$\mu_{\text{HAS\&TS}}^{DM}$	μ_{MOPSO}^{DM}	μ_{NSGA2}^{DM}
DM	0.05	0.331	34603093	28107633	811020246

Since the p-value is higher than 0.05, the assumption of equality in terms of the DM random variable can be accepted with a significant level of 5%. According to the results, the average DM is as the following, which indicates the better performance of the NSGA-II algorithm with a significant level higher than 33%.

$$\mu_{NSGA2}^{DM} > \mu_{\text{HAS\&TS}}^{\text{DM}} > \mu_{MOPSO}^{\text{DM}} \tag{52}$$

7-1-4- NPS (Number of Pareto front points) index

This index calculates the number of non-dominant solutions obtained by the algorithm. The higher the NPS index, the higher the priority of the algorithm.

Table 23. Results based on the NPS index

Problem Number	NPS			
	Gams	**NSGA-II**	**MOPSO**	**HSA&TS**
1	10	12	14	14
2	12	17	12	30
3	16	16	12	24
4	-	16	10	22
5	-	30	12	30
6	-	30	10	30
7	-	30	9	30
8	-	30	12	30
9	-	30	11	30
10	-	30	10	30
11	-	30	12	30
12	-	30	9	30

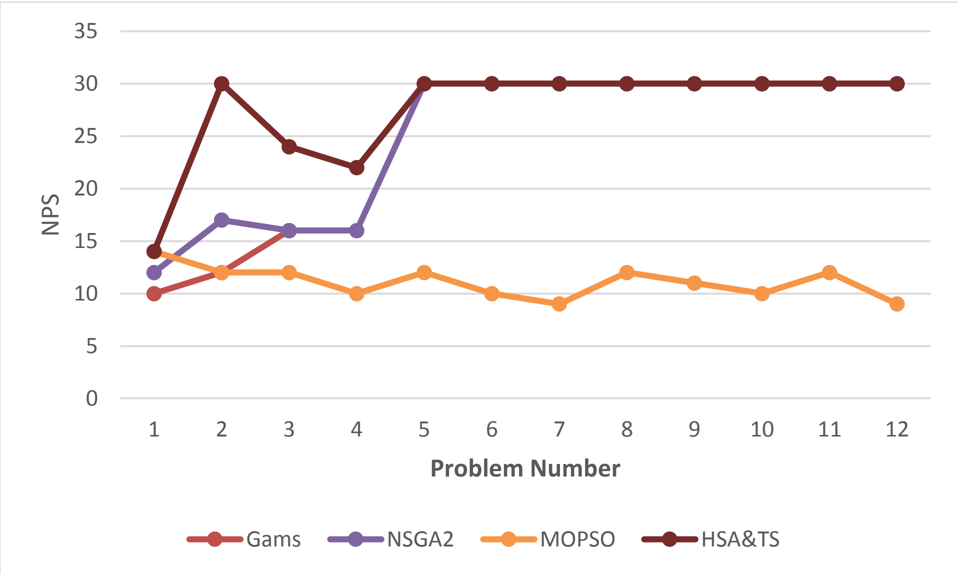

Fig 18. Results based on the NPS index

According to figure (18), HAS&TS is generally better than the other algorithms. This superiority is examined in detail with an ANOVA test. First, the equality assumption of the average communities of algorithms is presented as follows:

$$\begin{cases} H_0 : \mu^{NPS}_{\text{HAS\&TS}} = \mu^{NPS}_{MOPSO} = \mu^{NPS}_{NSGA2} \\ H_1 : \mu^{NPS}_{\text{HAS\&TS}} \neq \mu^{NPS}_{MOPSO} \neq \mu^{NPS}_{NSGA2} \end{cases} \tag{52}$$

The ANOVA output with a significant level of 0.05 is presented in the following table:

Table 24. One-way analysis of variance

index	α	P-value	$\mu^{NPS}_{\text{HAS\&TS}}$	μ^{NPS}_{MOPSO}	μ^{NPS}_{NSGA2}
DM	0.05	0.00001	27.5	11.083	25.08

Since the p-value is less than 0.05, the assumption of equality in terms of the NPS random variable cannot be accepted at the significant level of 5%. According to the results, the average NPS is as follows, which shows the better performance of the HAS&TS algorithm based on the NPS index.

$$\mu_{\text{HAS\&TS}}^{\text{NPS}} > \mu_{NSGA2}^{\text{NPS}} > \mu_{MOPSO}^{\text{NPS}} \tag{53}$$

5-1-5- Time(s) index

According to figure (13), it could be claimed that the HAS&TS algorithm outperformed the other algorithms. To make sure, however, an ANOVA test was conducted.

Table 25. Results based on the Time index

Problem Number	Time(s)			
	Gams	NSGA-II	MOPSO	HSA&TS
1	8.06	78.0668	83.4022	50.16004
2	20.74	97.1728	118.5242	67.8489
3	50.25	146.325	179.7802	96.5
4	-	163.0705	186.9665	77.95
5	-	273.4424	331.8746	202.65
6	-	437.6037	468.91	272.695011
7	-	526.74	708.2304	295.7596
8	-	744.2982	714.9996	544.076227
9	-	886.4086	956.878	562.75375
10	-	1740.37	1396.126	1224.806024
11	-	3026.386	2035.34	2085.999
12	-	2388.79	2102.656	2214.964

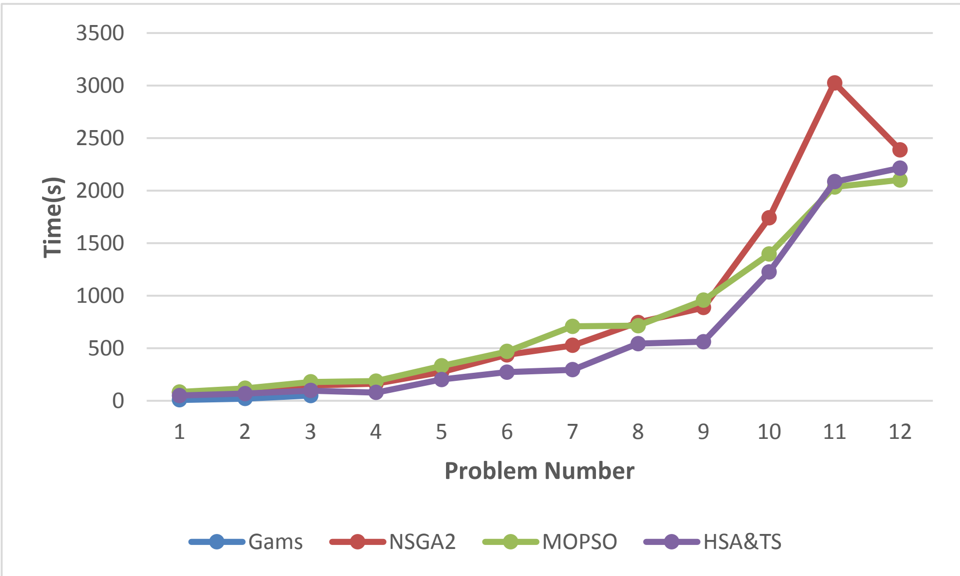

Fig19. Results based on the time index

First, the equality assumption for the average communities of algorithms is presented as follows:

$$\begin{cases} H_0 : \mu_{\text{HAS\&TS}}^{Time} = \mu_{MOPSO}^{Time} = \mu_{NSGA2}^{Time} \\ H_1 : \mu_{\text{HAS\&TS}}^{Time} \neq \mu_{MOPSO}^{Time} \neq \mu_{NSGA2}^{Time} \end{cases} \quad (54)$$

Accordingly, the ANOVA output with a significant level of 0.05 is as the following:

Table 26. One-way analysis of variance

index	α	P-value	$\mu_{\text{HAS\&TS}}^{Time}$	μ_{MOPSO}^{Time}	μ_{NSGA2}^{Time}
T	0.05	0.1808	641	774	876

Since the p-value is greater than 0.05, the equality assumption of the average can be accepted in terms of the Time random variable. Moreover, according to the results, the average Time is as the following (55), which demonstrates the better performance of the HAS&TS algorithm with a significant level higher than 18% based on the Time index.

$$\mu_{\text{HAS\&TS}}^{\textbf{Time}} < \mu_{MOPSO}^{\textbf{NPS}} < \mu_{NSGA2}^{\textbf{Time}} \quad (55)$$

8- Conclusion

This study has proposed a multi-objective mathematical model to design a closed-loop supply chain network for a specified fruit. The purpose is to reduce the supply chain costs and risks and increase the demand. This chain uses reverse logistics operations to recycle the waste of the fruit, such as the skin, into ethanol as a fuel for cars, a source of energy, and an organic fertilizer. In order to validate and test the designed model, a case study has been conducted of pomegranates in Iran. Moreover, to solve the mathematical model, the epsilon method of the generalized limit has been used through the GAMS software. As the results indicate, the problem has a suitable solution in small dimensions. Furthermore, in order to investigate the model in larger dimensions, the NSGA-II and MOPSO meta-heuristic algorithms and the HAS&TS hybrid algorithm serve to analyze the problem. According to the results of the proposed methods and the analysis of variance based on Time, NPS, MID and SNS indices, the HAS&TS algorithm outperforms the NSGA-II and MOPSO algorithms. However, the NSGA-II algorithm outperforms with DM indices. It is recommended that some parameters of the problem be considered non-deterministic, and different methods such as robust optimization and probabilistic programming be applied to control the uncertainty of the data. Future studies may also find it of value to consider a fuzzy system to predict uncertain demands for pomegranates, modify the model proposed in this study into a scenario-based model and solve it with a robust optimization approach, and apply cooperative games between pomegranate producers and the government with a game theory.

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