Sustainable pomegranate supply chain network design considering cultivation process and water consumption

Mohammad Pourmehdi
Department of High-Tech Business and Entrepreneurship, University of Twente, Enschede, The Netherlands

Seyed Hossein Hosseinian-Kashani
Department of Industrial Engineering, Babol Noshirvani University of Technology, Babol, Iran

Mohammad Mahdi Paydar*
Department of Industrial Engineering, Babol Noshirvani University of Technology, Babol, Iran

Ali Divsalar
Department of Industrial Engineering, Babol Noshirvani University of Technology, Babol, Iran

Abstract
Agricultural activities have adverse effects on the environment by emitting greenhouse gases and consuming great deals of freshwater. In addition, fruits constitute a substantial part of agricultural products used for balancing diets. In particular, pomegranate is one of the most used products by people of different cultures. In this study, a multi-objective mathematical model was developed to balance sustainability dimensions by focusing on selecting the optimal cultivation process and determining the optimal material flows between pomegranate supply chain facilities. The proposed model maximizes the total profit and the number of created job opportunities due to cultivation process selection and the establishment of plants. It also addresses the environmental impacts by minimizing fertilizer, pesticide, and water consumption in pomegranate cultivation. The model also considers the reverse flow of pomegranate peel and seeds to recapture the value of these products, commonly known as waste. A real case in the Mazandaran province of Iran was considered for validating the developed model. Finally, comprehensive sensitivity analyses were performed on the influential factors of the problem, and managerial implications are presented.

Keywords: Sustainability, Agricultural supply chain, Forward and reverse flows, Pomegranate, Cultivation process, Water consumption

1. Introduction
One of the most significant sectors of the economy in both developed and developing countries is agriculture, which influences food supply, health, and political issues besides the economy [1]. Moreover, the agricultural supply chain has attracted the attention of practitioners and researchers due to its unique characteristics, including the significance of food quality and changes in the price, climate, and demand for various types of food [2]. Furthermore, because of the significant role of agriculture in the economy, society, and environment, next to government regulations and environmental awareness, the design and application of efficient supply chain networks considering sustainability dimensions have caught the attention of researchers during the past few years.
The agricultural sector negatively impacts the environment, as it has been reported to be the largest consumer of freshwater and the second-largest emitter of greenhouse gases in the world. The share of agriculture in global greenhouse emission and the trend of renewable freshwater resources for top agricultural countries, highlight the mentioned reasons for considering the environmental aspects of agriculture [3]. Moreover, the intense consumption of pesticides and fertilizers in agriculture can lead to the emission of greenhouse gasses, such as nitrous oxide and methane, to the various media in the ecosphere, including air, soil, and water, contaminating the natural resources and threatening the health of the population. Conversly, agriculture also positively affects society and the economy, providing an essential and significant source of income, employment, and food, especially for the rural population of the world. These issues highlight the importance of creating a balance between the sustainability dimensions in the agricultural sector.
Moreover, the reverse flow of materials would lead to attaining additional value from the materials commonly known as waste [4]. In some industries, based on the characteristics of the products, the collected wastes could enter

* Corresponding author, paydar@nit.ac.ir; Phone: 00989113235979

their own or other supply chain networks as raw materials [5]. Therefore, the reverse flow of materials would influence the social and environmental dimensions of sustainability, in addition to attaining profit from the process.
The pomegranate fruit grows on the native fruit-bearing deciduous shrub in Iran and Afghanistan, now being cultivated worldwide. The demand for pomegranate and its products and by-products is growing globally due to its health-promoting effects on the human diet and multifunctional characteristics. The pomegranate fruit is composed of two main parts, including the arils and peel, each of which has about fifty percent of the weight of the whole fruit. The arils are divided into seeds and juice, with about twenty and thirty percent of the fruit's weight, respectively [6].
Generally, fruits play a significant role in creating balanced diets and supplying various types of nutrients that promote human health. In particular, pomegranate has been reported to be one of the most favoured products in different cultures for centuries, maintaining health and treating various health conditions. Pomegranate peels are also the source of various nutrients and minerals, and arils contain sugar and organic acids, in addition to water. Pomegranate seeds contain vitamins, fibers, proteins, and sugar, and pomegranate seed oil is characterized by a high content of different organic acids [7]. The numerous benefits of pomegranates, which are explored briefly above, indicate the reason for its growing demand worldwide and its various uses in different products and industries.
Due to the growing demand for pomegranate products and by-products, this study was conducted, in which a sustainable pomegranate supply chain network considering different cultivation processes was designed. Since it is suggested to recapture the value of pomegranate seeds and peels, which are commonly considered waste, both forward and reverse material flows in the supply chain were investigated. The primary objective of this study was to create a balance between sustainability dimensions by determining the cultivation process of pomegranate and the flow of materials between elements of the supply chain. The optimal results of this study would consist of maximizing the total profit of the network and the number of created job opportunities as a consequence of the selection of cultivation processes and the establishment of potential centers. Moreover, the model minimizes the consumption of fertilizers and pesticides to reduce the emitted greenhouse gases, and also minimizes water consumption by considering the provided water from rainfall and the influence of irrigation on the pomegranate harvesting rate. Finally, the Improved Multi-Choice Goal Programing (IMCGP) approach was used as the solution technique.

2. Related studies

Allaoui et al. [8] presented a multi-objective mathematical model (MOMM) for optimizing an agro-food supply chain network design and addressing carbon and water footprints, the number of created jobs, and the total costs. A study with the primary goal of analyzing the role of public health, demand substitution, and climate change in designing a sustainable supply chain network for conventional and organic agro-food was done by Sazvar et al. [9]. In this study, an MOMM was developed to balance the consumption and production of organic and conventional food to reduce costs and environmental degradation, while also increasing the health levels of customers. Cheraghalipour et al. [10] proposed an MOMM for the closed-loop supply chain of citrus fruits. They developed the multi-objective Keshtel algorithm to minimize total costs and maximize demand responsiveness for forward and reverse flows.
Banasik et al. [11] presented an MOMM combined with two-stage stochastic programming for analyzing environmental and economic aspects of a mushroom supply chain in the Netherlands. Roghanian and Cheraghalipour [12] focused on using a set of meta-heuristic algorithms to optimize a closed-loop citrus supply chain through their developed MOMM aiming to minimize carbon dioxide emissions and total costs and maximize demand responsiveness. A study focusing on minimizing total costs of a real case problem of wheat supply chain in Iran considering parameter uncertainty was done by Hosseini-Motlagh et al. [13]. Cheraghalipour et al. [14] addressed the rice supply chain and proposed a bi-level mathematical model to minimize total costs. They used several meta-heuristic algorithms and their integration to solve the bi-level model.
Mogale et al. [15] proposed a bi-objective mathematical model addressing sustainable food grain supply chain minimizing carbon dioxide emission and total costs simultaneously. Jabarzadeh et al. [16] developed an MOMM for a closed-loop supply chain network of perishable agricultural products aiming to balance carbon dioxide emissions, total costs, and demand responsiveness. A study presenting an MOMM for sustainable wheat supply chain aiming to minimize water consumption and total costs and maximize created job opportunities was done by Motevalli-Taher et al. [17]. Chavez et al. [18] presented an MOMM integrated with stochastic programming for a sustainable sugarcane supply chain considering harvest, maintenance, and transportation. Liao et al. [19] developed a mixed-integer linear mathematical model for a closed-loop supply chain of citrus, minimizing carbon taxes on production and transportation emissions and total costs. They used a set of meta-heuristics algorithms and their hybrid forms to solve their model. Hosseini-Motlagh et al. [20] developed an MOMM for a wheat supply chain design to minimize negative impacts of social responsibility, non-resiliency, and total costs in an uncertain environment. A study

developing a mixed-integer linear model for a food grains supply chain aiming to minimize total costs through the specification of the location and number of procurement centers was done by Mogale et al. [21].
Keshavarz-Ghorbani and Pasandideh [22] formulated a bi-objective mixed-integer linear model for the agro supply chain of apples to minimize carbon dioxide emissions and total costs. Kazemi et al. [23] formulated a bi-objective mathematical model for the rice supply chain minimizing the soil erosion through water consumption and total costs of the network. In one of the latest studies that presented mathematical models for the design of agricultural supply chains, Salehi-Amiri et al. [24] developed a mixed-integer linear model for a walnut closed-loop supply chain, minimizing the total costs of the network, considering both forward and reverse flows.
The number of studies that considered the social and environmental dimensions of agricultural supply chains besides the economic aspect is increasing in the past few years. However, some studies presented general models, and some considered a specific crop or fruit and designed their network, taking into account their specifications. Each study addressed different aspects of sustainability for their considered problem, and yet it appears that some significant issues have been neglected. Therefore, there seems to be a gap for thorough research addressing the pomegranate supply chain considering different aspects of sustainability dimensions specific to this fruit. This study fills the gap, presenting a multi-objective mixed-integer linear programming model for a pomegranate supply chain network design considering various cultivation processes and forward and reverse flow of material and products and their impacts on sustainability dimensions. The significance of the present study is outlined in the following bullets.

- Based on the literature on agricultural supply chains, there is no study addressing the existing research gap. Hence, the present study designs the first supply chain network in the literature compatible with specific characteristics of pomegranate.
- The consumption of fertilizer and pesticides in the pomegranate cultivation process and their impact on the sustainability dimensions are addressed in this research. To the best of our knowledge, this is the first study modeling the use of fertilizers and pesticides in the cultivation process, mathematically.
- Irrigation is considered in the cultivation process, not as a necessary action similar to some previous studies. Irrigation has a positive impact on the harvesting rate of pomegranate trees. Hence, it is decided by farmers to irrigate their farms or not. It is also assumed that the provided water by precipitation could be used in irrigation.
- The by-products of the production process in processing and hybrid plants are considered to be the raw materials of various industries according to their specifications to address the reverse flow of material to the network and recapture the value of these products that are commonly known as waste.
- A real case study of the pomegranate supply chain is considered in Iran as one of the major pomegranate producers in the world to validate the presented model. Various sensitivity analyses are performed to specify the role of each element of the model on the final results, and managerial insights are presented.

3. Problem description

The proposed sustainable pomegranate supply chain network consists of suppliers (farms and import centers), production plants (processing and hybrid (processing and packaging) plants), packaging plants, and several types of markets for each product and by-product of the network. In addition, two of the considered markets are suppliers of other supply chain networks themselves. A short description of each facility of the supply chain is presented in the following.

- Farm (Supplier type 1): where pomegranate is cultivated and harvested using different cultivation processes.
- Import center (Supplier type 2): where pomegranate would be imported from outside of the network (farms outside of the network, which could be in other cities, provinces, or countries based on the scale of the problem).
- Processing plant (Production plant type 1): where processed products and the by-products of the production process are produced based on some processes done on pomegranate.
- Hybrid plant (Production plant type 2): where the operational processes of the plant are similar to processing plant with the added ability to package a part of its produced products.
- Packaging plant: where the produced products would be packaged.
- Market for processed products (Market type 1): supermarkets and stores.
- Market for pomegranate peel (Market type 2): animal husbandry where animals consume the pomegranate peel as feed. This market could be considered as the supplier for the meat and dairy industry.

- Market for pomegranate seeds (Market type 3): pomegranate seed oil producers. Due to the numerous benefits of pomegranate seed oil, it is used in various industries, changing the role of oil producers to suppliers for other networks.
- Market for pomegranate fruit (Market type 4): fresh fruit markets.

Pomegranate is supplied from farms and import centers. Farmers can use different kinds of cultivation processes, selecting them based on the characteristics of the farm, including the soil characteristics, the type of tree they have, and rainfall. Other reasons such as the amount of cost they would be willing to pay for the cultivation process and the amount of pomegranate they predict to harvest according to the selected process may influence the decision in choosing the cultivation processes. The primary difference in cultivation processes is in the type and the amount of fertilizers and pesticides used in the process and the amount of water that farmers have to use for irrigation in each cultivation process. All these decisions may impact the cost of the process and the amount of harvesting pomegranate.

Since the harvested pomegranate from inside of the network might not be sufficient to meet the demand of the markets, the import centers are considered to solve the potential pomegranate supply issue. The supplied pomegranates then could go through the production process, which is processing and packaging, or be sent to the fresh fruit market. When the pomegranate goes with the first choice, there are two types of facilities to go through. The first type is the processing plants, and since these plants do not have the required equipment for packaging the processed products, their final products will be sent to packaging plants. The second type is hybrid plants, where the pomegranate can be transformed into processed products, get packaged, and become ready for transportation to the final market. The packaging capacity of hybrid centers might be lower than their production capacity, and due to that, they may send the surplus of processed products to packaging plants. The packaging plants package the products received from processing and hybrid plants. Finally, the packaged products will be transported to their market from hybrid and packaging plants. Processing and hybrid plants can produce various types of processed products, such as pomegranate molasses (paste), juice, vinegar, and jam. All parts of pomegranate are used and transformed into various products, and no part is wasted. In the production plants, the juice of pomegranate is separated from its peel and seeds. The juice is then used for producing different kinds of processed products, and the peel and seeds are the by-products of the production process. The peel is transported to animal husbandry, where it is used as feed for livestock. Seeds are transported to pomegranate oil producers, where they are processed to pomegranate seed oil. The structure of the addressed network consisting of different facilities and the flow between them is shown in Fig 1.

3.1. Notations

Indices:

o	Cultivation processes
i	Farms (suppliers type 1)
j	Import centers (suppliers type 2)
k	Processing plants (production plants type 1)
l	Hybrid plants (production plants type 2)
m	Packaging plants

Parameters:

rpp	Selling price of processed product
rp	Selling price of pomegranate peel
rs	Selling price of pomegranate seeds
rf	Selling price of fresh pomegranate
pi_{io}	Cultivation cost of pomegranate in farm i using cultivation process o
pr_{io}	Harvesting rate of pomegranate in farm i using cultivation process o
vi_i	Maximum capacity of farm i for cultivating pomegranate
pj_j	Purchasing cost of pomegranate from import center j
vj_j	Maximum capacity of import center j for providing pomegranate
cik_{ik}	Transportation cost of pomegranate from farm i to processing plant k
cil_{il}	Transportation cost of pomegranate from farm i to hybrid plant 1
ci_i	Transportation cost of pomegranate from farm i to market type 4
cjk_{jk}	Transportation cost of pomegranate from import center j to processing plant k
cjl_{jl}	Transportation cost of pomegranate from import center j to hybrid plant l
cj_j	Transportation cost of pomegranate from import center j to fresh fruit market
pk_k	Production cost of processed product in processing plant k
pl_l	Production cost of processed product in hybrid plant l

pp_l	Packaging cost of processed product in hybrid plant *l*
pm_m	Packaging cost of processed product in packaging plant *m*
β	Transformation rate of pomegranate to processed product
γ	Transformation rate of pomegranate to pomegranate peel
λ	Transformation rate of pomegranate to pomegranate seeds
vk_k	Maximum production capacity of processing plant *k*
vl_l	Maximum production capacity of hybrid plant *l*
vpl_l	Maximum packaging capacity of hybrid plant *l*
vm_m	Maximum packaging capacity of packaging plant *m*
ckm_{km}	Transportation cost of processed product from processing plant *k* to packaging plant *m*
clm_{lm}	Transportation cost of processed product from hybrid plant *l* to packaging plant *m*
$ck2_k$	Transportation cost of pomegranate peel from processing plant *k* to market type 2
$ck3_k$	Transportation cost of pomegranate seeds from processing plant *k* to market type 3
$cl1_l$	Transportation cost of packaged product from hybrid plant *l* to market type 1
$cl2_l$	Transportation cost of pomegranate peel from hybrid plant *l* to market type 2
$cl3_l$	Transportation cost of pomegranate seeds from hybrid plant *l* to market type 3
cm_m	Transportation cost of packaged product from packaging plant *m* to market type 1
$d1$	Demand of market type 1 for processed product
$d2$	Demand of market type 2 for pomegranate peel
$d3$	Demand of market type 3 for pomegranate seeds
$d4$	Demand of market type 4 for fresh pomegranate
fo_{io}	Fixed cost of using cultivation process *o* in farm *i*
fe_l	Fixed cost of establishing potential hybrid plant *l*
fc_{io}	Required amount of fertilizer in using cultivation process *o* in farm *i*
pc_{io}	Required amount of pesticide in using cultivation process *o* in farm *i*
wre_{io}	Required amount of water for irrigation in using cultivation process *o* in farm *i*
rw_i	The ratio of required water provided by rain in farm *i*
$maxf_o$	Maximum amount of fertilizer consumption in cultivation process *o*
$maxp$	Maximum amount of pesticide consumption
$maxw$	Maximum amount of water consumption
wef_{io}	Given weight to fertilizer consumption in using cultivation process *o* in farm *i*
wep_{io}	Given weight to pesticide consumption in using cultivation process *o* in farm *i*
wew_{io}	Given weight to water consumption for irrigation in using cultivation process *o* in farm *i*
jc_{io}	Number of job opportunities created in using cultivation process *o* in farm *i*
je_l	Number of job opportunities created in establishing potential hybrid center *l*
MB	A big number

Variables:

Z_{io}	Area under pomegranate cultivating in farm *i* using cultivation process *o*
MI_{io}	Manual irrigation in farm *i* using cultivation process *o*
Q_j	Imported pomegranate from import center *j*
ZK_{ik}	Transported pomegranate from farm *i* to processing plant *k*
ZL_{il}	Transported pomegranate from farm *i* to hybrid plant l
$Z4_i$	Transported pomegranate from farm *i* to market type 4
QK_{jk}	Transported pomegranate from import center *j* to processing plant *k*
QL_{jl}	Transported pomegranate from import center *j* to hybrid plant *l*
$Q4_j$	Transported pomegranate from import center *j* to market type 4
YM_{km}	Transported processed product from processing plant *k* to packaging plant *m*
$Y2_k$	Transported pomegranate peel from processing plant *k* to market type 2
$Y3_k$	Transported pomegranate seeds from processing plant *k* to market type 3
$W1_m$	Transported packaged product from packaging plant *m* to market type 1
XM_{lm}	Transported processed product from hybrid plant *l* to packaging plant *m*
$X1_l$	Transported packaged product from hybrid plant *l* to market type 1
$X2_l$	Transported pomegranate peel from hybrid plant *l* to market type 2
$X3_l$	Transported pomegranate seeds from hybrid plant *l* to market type 3
OI_{io}	1 if cultivation process *o* is used for cultivating pomegranate in farm *i*, otherwise 0
G_l	1 if potential hybrid plant *l* is established, otherwise 0

3.2. Mathematical model

Economic objective function:

$$Max\ Obj1 = R1 - \left(C1 + C2 + C3\right) \tag{1}$$

Revenue:

$$R1 = rpp \times \left(\sum_{m} W1_m + \sum_{l} X1_l\right) + rp \times \left(\sum_{k} Y2_k + \sum_{l} X2_l\right) + rs \times \left(\sum_{k} Y3_k + \sum_{l} X3_l\right) + rf \times \left(\sum_{i} Z4_i + \sum_{j} Q4_j\right) \tag{2}$$

Operational costs:

$$\begin{aligned} C1 = &\sum_{i}\sum_{o} pi_{io} \times pr_{io} \times Z_{io} + \sum_{j} pj_j \times Q_j + \sum_{k} pk_k \times \left(\sum_{i} ZK_{ik} + \sum_{j} QK_{jk}\right) \\ &+ \sum_{l} pl_l \times \left(\sum_{i} ZL_{il} + \sum_{j} QL_{jl}\right) + \sum_{l} pp_l \times X1_l + \sum_{m} pm_m \times \left(\sum_{k} YM_{km} + \sum_{l} XM_{lm}\right) \end{aligned} \tag{3}$$

Transportation costs:

$$\begin{aligned} C2 = &\sum_{i}\sum_{k} cik_{ik} \times ZK_{ik} + \sum_{i}\sum_{l} cil_{il} \times ZL_{il} + \sum_{i} ci_i \times Z4_i + \sum_{j}\sum_{k} cjk_{jk} \times QK_{jk} \\ &+ \sum_{j}\sum_{l} cjl_{jl} \times QL_{jl} + \sum_{j} cj_j \times Q4_j + \sum_{k}\sum_{m} ckm_{km} \times YM_{km} + \sum_{l}\sum_{m} clm_{lm} \times XM_{lm} \\ &+ \sum_{k} ck2_k \times Y2_k + \sum_{k} ck3_k \times Y3_k + \sum_{l} cl1_l \times X1_l + \sum_{l} cl2_l \times X2_l + \sum_{l} cl3_l \times X3_l + \sum_{m} cm_m \times W1_m \end{aligned} \tag{4}$$

Fixed costs:

$$C3 = \sum_{i}\sum_{o} fo_{io} \times OI_{io} + \sum_{l} fe_l \times G_l \tag{5}$$

The first objective function maximizing the total profit is represented in Equation (1). The objective function addresses the economic aspects of the supply chain consisting of four terms being revenue and operational, transportation, and fixed costs. Equation (2) computes the earned revenue from selling processed products, pomegranate peel, pomegranate seeds, and fresh fruit to their specific markets. Equation (3) calculates the cultivation cost of pomegranate in farms, the purchasing cost of pomegranate from import centers, the production cost of processed products in processing and hybrid plats, the packaging cost of processed products in hybrid and packaging plants are computed respectively. Equation (4) computes the transportation cost of pomegranate, processed products, and pomegranate peel and seeds between facilities of the supply chain. Finally, fixed costs of using cultivation processes and opening potential hybrid plants are calculated in Equation (5).

Environmental objective function:

$$Min\ Obj2 = E1 + E2 + E3 \tag{6}$$

$$E1 = \sum_{i}\sum_{o} \frac{wef_{io} \times fc_{io} \times Z_{io}}{maxf_o} \tag{7}$$

$$E2 = \frac{1}{maxp} \times \sum_{i}\sum_{o} wep_{io} \times pc_{io} \times Z_{io} \tag{8}$$

$$E3 = \frac{1}{maxw} \times \sum_{i}\sum_{o} wew_{io} \times MI_{io} \tag{9}$$

The second objective function minimizing the negative environmental impacts of using different cultivation processes is shown in Equation (6). It is the weighted sum of the normalized impact of three different materials in chosen cultivation processes. Equation (7) computes the weighted normalized amount of different types of used fertilizers in different cultivation processes. The weighted normalized amounts of pesticide and water consumed in different cultivation processes are calculated in Equations (8) and (9), respectively.

Social objective function:

$$Max\ Obj3 = \sum_{i}\sum_{o} jc_{io} \times Z_{io} + \sum_{l} je_l \times G_l \tag{10}$$

The third objective function, represented in Equation (10), maximizes the social aspects of the operations of the supply chain. The objective function computes the number of job opportunities created using different cultivation processes and the establishment of potential hybrid plants.

Constraints:

Cultivation process constraints:

$$\sum_{o} OI_{io} \le 1 \qquad \forall i \tag{11}$$

$$Z_{io} \le MB * OI_{io} \qquad \forall i,o \tag{12}$$

$$\left(wre_{io}\left(1 - rw_i\right)\right) \times Z_{io} = MI_{io} \qquad \forall i,o \tag{13}$$

Equations (11) and (12) guarantee that only one cultivation process would be selected and used in each farm. Equation (13) shows that a part of the water required for irrigation in the selected cultivation process could be provided by rainfall.

Capacity constraints:

$$\sum_{o} Z_{io} \le vi_i \qquad \forall i \tag{14}$$

$$Q_j \le vj_j \qquad \forall j \tag{15}$$

$$\beta \times \left(\sum_{i} ZK_{ik} + \sum_{j} QK_{jk} \right) \le vk_k \qquad \forall k \tag{16}$$

$$\beta \times \left(\sum_{i} ZL_{il} + \sum_{j} QL_{jl} \right) \le G_l \times vl_l \qquad \forall l \tag{17}$$

$$\beta \times \left(\sum_{i} ZL_{il} + \sum_{j} QL_{jl} \right) - \sum_{m} XM_{lm} \le G_l \times vpl_l \qquad \forall l \tag{18}$$

$$\sum_{k} YM_{km} + \sum_{l} XM_{lm} \le vm_m \qquad \forall m \tag{19}$$

Equation (14) guarantees that the land used for the cultivation process will not surpass the hectares of each farm. Each import center cannot import pomegranate more than its specified capacity, ensured by Equation (15). Equation (16) guarantees that the amount of processed products in each processing plant is limited by its production capacity. Equations (17) and (18) ensure that only the established hybrid centers can produce and package a specified amount of processed products restricted by their limited capacity. The packaging plants can package a specific amount of processed products limited to their packaging capacity, ensured by Equation (19).

Flow and balance constraints:

$$\sum_{o} pr_{io} \times Z_{io} = \sum_{k} ZK_{ik} + \sum_{l} ZL_{il} + Z4_i \qquad \forall i \tag{20}$$

$$Q_j = \sum_{k} QK_{jk} + \sum_{l} QL_{jl} + Q4_j \qquad \forall j \tag{21}$$

$$\beta \times \left(\sum_{i} ZK_{ik} + \sum_{j} QK_{jk} \right) = \sum_{m} YM_{km} \qquad \forall k \tag{22}$$

$$\gamma \times \left(\sum_{i} ZK_{ik} + \sum_{j} QK_{jk} \right) = Y2_k \qquad \forall k \tag{23}$$

$$\lambda \times \left(\sum_{i} ZK_{ik} + \sum_{j} QK_{jk} \right) = Y3_k \qquad \forall k \tag{24}$$

$$\beta \times \left(\sum_i ZL_{il} + \sum_j QL_{jl} \right) = X1_l + \sum_m XM_{lm} \qquad \forall l \tag{25}$$

$$\gamma \times \left(\sum_i ZL_{il} + \sum_j QL_{jl} \right) = X2_l \qquad \forall l \tag{26}$$

$$\lambda \times \left(\sum_i ZL_{il} + \sum_j QL_{jl} \right) = X3_l \qquad \forall l \tag{27}$$

$$\sum_k YM_{km} + \sum_l XM_{lm} = W1_m \qquad \forall m \tag{28}$$

$$\sum_m W1_m + \sum_l X1_l \le d1 \tag{29}$$

$$\sum_k Y2_k + \sum_l X2_l \le d2 \tag{30}$$

$$\sum_k Y3_k + \sum_l X3_l \le d3 \tag{31}$$

$$\sum_i Z4_i + \sum_j Q4_j \le d4 \tag{32}$$

Equations (20) and (21) guarantee the equality of the amount of harvested pomegranate from farms and imported pomegranate from import centers to the amount of pomegranate transported from them to processing and hybrid plants and fresh fruit market. The equality of processed products transported from processing to packaging plants is ensured by Equation (22). Equations (23) and (24) guarantee the equality of transported pomegranate peel and seeds, produced as by-products of the production process, from processing plants to their specified markets. The equality of produced processed products in hybrid plants to the amounts of processed products transported to packaging plants and packaged products transported to their specific market is guaranteed by Equation (25). Equations (26) and (27) do the same thing as Equations (23) and (24) only for hybrid plants. The equality of inflow and outflow of processed products to and from packaging plants is ensured by Equation (28). Equations (29)-(32) guarantee that the amounts of transported packaged products, pomegranate peel and seeds, and fresh fruits to their specific markets are less than or equal to their demand.
Variable type constraint:

$$Z_{io}, MI_{io}, Q_j, ZK_{ik}, ZL_{il}, Z4_i, QK_{jk}, QL_{jl}, Q4_j, YM_{km}, Y2_k, Y3_k, W1_m, XM_{lm}, X1_l, X2_l, X3_l \ge 0 \tag{33}$$

$$OI_{io}, G_l \in \{0,1\} \tag{34}$$

Equations (33) and (34) show the types of decision variables.

4. Solution approach

In many real case problems, decision-makers need to address more than one objective function simultaneously. Each of these objective functions would represent a specific solution, which most probably contradicts each other when optimized separately. In situations like this, multi-objective optimization techniques would be recommended to solve the problems [25].One of the most practical and well-known techniques addressing multi-objective problems is the Goal Programming (GP). All different versions of GP approaches have a similar goal minimizing the deviations from the determined aspiration levels. Although presenting aspiration levels for objective functions based on the available data and the existing limitations might be challenging. To alleviate the pressure off of the decision-makers regarding this, Chang [26] introduced the multi-choice GP approach, where decision-makers are allowed to suggest multiple aspiration levels for a specific objective function.
Subsequently, Jadidi et al. [27] proposed a method taking into account the merits of the revised GP and the GP with utility functions and called it IMCGP. They suggested considering an interval as the aspiration levels instead of specific numbers to take into account the cases that the objective functions get a value worse than the determined aspiration levels and assigned a penalty to these cases. They divided the aspiration interval into two parts, namely, the more desirable range (MDR) and the less desirable range (LDR). It is assumed that $u \in \{1,2,\ldots,Ui\}$ and

$u\epsilon$ {Ui+1,…,U} are set of maximizing and minimizing objective functions, respectively. The IMCGP approach and the required notions are presented in the following.

Index:

u Index of objective functions

Parameters:

wa_u Given weight to objective function u in the MDR

wb_u Given weight to objective function u in the LDR (penalty)

go_u^+ Best value that objective function u can get

go_u^- Worst value that objective function u can get

$go_{u,min}$ Upper bound of the LDR for objective function $u\epsilon$ {$1,2,…,Ui$}

$go_{u,max}$ Lower bound of the LDR for objective function $u\epsilon$ {$Ui+1,…,U$}

Variables:

a_u Normalized distance from the lower bound of the MDR for objective function $u\epsilon$ {$1,2,…,Ui$} and the upper bound of the MDR for objective function $u\epsilon$ {$Ui+1,…,U$}

b_u Normalized distance from the upper bound of the LDR for objective function $u\epsilon$ {$1,2,…,Ui$} and the lower bound of the LDR for objective function $u\epsilon$ {$Ui+1,…,U$}

y_u Binary auxiliary variable

Based on the above explanations, the general form of the IMCGP is as follows:

$$Maz\ ZGP = \sum_u \left(wa_u \times a_u - wb_u \times b_u \right) \quad (35)$$

s.t.

$$h_c(X) = (\leq or \geq) 0 \qquad \forall c \quad (36)$$

$$f_u(X) = a_u \times go_u^+ + (1-a_u) \times go_{u,min} + b_u \times \left(go_u^- - go_{u,min} \right) \qquad \forall u = (1,2,...,Ui) \quad (37)$$

$$f_u(X) = a_u \times go_u^+ + (1-a_u) \times go_{u,max} + b_u \times \left(go_u^- - go_{u,max} \right) \qquad \forall u = (Ui+1,...,U) \quad (38)$$

$$a_u \leq y_u \leq 1 + a_u \qquad \forall u = (1,2,...,U) \quad (39)$$

$$b_u + y_u \leq 1 \qquad \forall u = (1,2,...,U) \quad (40)$$

$$0 \leq a_u, b_u \leq 1 \qquad \forall u = (1,2,...,U) \quad (41)$$

$$y_u \in \{0,1\} \qquad \forall u = (1,2,...,U) \quad (42)$$

Equation (35) shows the goal of the IMCGP maximizing the weighted normalized distance of maximizing objective functions from $go_{u,min}$, and minimizing objective functions from $go_{u,max}$, and simultaneously minimizing the penalty. The constraints of the main problem are presented in Equation (36). Equations (37) and (38) calculate the value of each objective function. $h_c(X)$ and $f_u(X)$ stand for system constraints and the variable of the objective function u, respectively. Equations (39) and (40) guarantee that when a_u>0, b_u=0 and when b_u>0, a_u=0, indicating that when a_u>0, the objective function is in the MDR and when b_u>0, the objective function is in the LDR, and a penalty would be considered. The decision variables are defined in Equations (41) and (42). The proposed multi-objective model after applying the explored IMCGP method changes as follows.

$$Max\,ZGP = wa_1 \times a_1 + wa_2 \times a_2 + wa_3 \times a_3 - wb_1 \times b_1 - wb_2 \times b_2 - wb_3 \times b_3 \quad (43)$$

s.t.

$$Obj1 = a_1 \times go_1^+ + (1-a_1) \times go_{1,min} + b_1 \times \left(go_1^- - go_{1,min} \right) \quad (44)$$

$$Obj2 = a_2 \times go_2^+ + (1-a_2) \times go_{2,max} + b_2 \times \left(go_2^- - go_{2,max} \right) \quad (45)$$

$$Obj3 = a_3 \times go_3^+ + (1-a_3) \times go_{3,min} + b_3 \times \left(go_3^- - go_{3,min} \right) \quad (46)$$

$$a_u \leq y_u \leq 1 + a_u \qquad \forall u = 1,2,3 \quad (47)$$

$$b_u + y_u \leq 1 \qquad \forall u = 1,2,3 \quad (48)$$

$$0 \leq a_u, b_u \leq 1 \qquad \forall u = 1,2,3 \quad (49)$$

$y_u \in \{0,1\}$ $\forall u = 1,2,3$ (50)

Constraints (11)-(34) (51)

5. Case study

A real case study from the Mazandaran province of Iran is used to indicate the validation of the presented model. The primary focus of the case study is on the transformation of pomegranate to pomegranate molasses as one of the widely used final products of pomegranate fruit in Iran and especially in Mazandaran. In the case study, the pomegranate fruit can be provided by the cultivation process in different farms or be imported to the network from other provinces that cultivate a great deal of pomegranate in Iran. Farmers can use different processes to cultivate pomegranate in their farms, selecting them based on the characteristics of their farms, the amount of cost they would be willing to pay for the process, and the amount of pomegranate they want to harvest. The difference in cultivation processes is in the type and the amount of fertilizers and the amount of pesticide and water that farmers have to use in each cultivation process. These decisions affect the cost of the process and the amount of harvesting pomegranate. Twenty different cultivation processes are considered for the case study based on the use of two different types of fertilizers in different amounts and the use of pesticides and irrigation. The details of each cultivation process are illustrated in Fig 2. For instance, in cultivation process 6, the row for manure specifies 50%, meaning that 50% of the specified manure, which is 10 tonnes based on the legend of Fig 2, should be used in this cultivation process. There is a check symbol in the row for irrigation, and there is no check in the row for pesticide, meaning that cultivation process 6 requires irrigation but not pesticide.

The pomegranate is harvested from farms or imported from other provinces through import centers. Then, the provided pomegranate is divided into two parts. One part is sent to the fresh fruit market, and the other part goes through the production processes to be transferred into pomegranate molasses and the by-products of the production process. There are two different types of production plants transforming pomegranate fruit into pomegranate molasses. Production plant type 1 or processing plant only produces molasses, but production plant type 2 or hybrid plant produces molasses and packages the product making it ready for the market. All of the produced molasses by processing plants and the part of produced molasses that would not get packaged in the hybrid plant due to its limited packaging capacity are sent to packaging plants to become ready for market. It is assumed that there are some potential locations for establishing new hybrid plants, too.

When pomegranates arrive at each plant, the pomegranate peel and arils are separated. The peel is sold to animal husbandry. The arils are turned into pomegranate juice and seeds. The pomegranate juice is used to produce molasses, and the seeds are sent to pomegranate seed oil produces. The number of different elements and the location of facilities of the discussed case are presented in Table 1 and Fig 3. It also should be mentioned that there are four hubs selected for each market type. Babol is the hub for market type 1, Amol is the hub for market type 2, and Isfahan is the hub for market types 2 and 3.

5.2. Results

There are some parameters in the solution approach to be set before solving the model. Each objective function of the model is solved separately to determine the best value for these parameters. Based on the results from solving each objective function separately and the opinion of decision-makers, the upper and lower bounds of each objective function and their given weight are determined and presented in Table 2.

The proposed model is solved using the described IMCGP approach, and the outcome is presented in detail in the following. The obtained value of each objective and the decision variables of the IMCGP are presented in Fig 4, where the green vertical line and the value written on top of it specify the location and the value taken by each objective in the corresponding range. Based on the results, the selected cultivation process for all farms is cultivation process 10, none of the potential hybrid plants is established, and market type 1 has 50 tonnes of unmet demand for pomegranate molasses, which is 6.2% of the total demand.

The values of composing elements of the environmental objective function are presented in Table 3. Since the total required water for irrigation based on the size of farms and the selected cultivation process is 74,430,000 liter, the value of used water for irrigation mentioned in Table 3 indicates that about 34% of the required water for irrigation is supplied by rainfall. Fig 5 depicts different parts of earned revenue from selling products and by-products of the supply chain. It can be noted that the biggest portion of earned revenue is acquired from selling the fresh fruit to market type 4, and the second biggest portion is the earned revenue from selling pomegranate molasses to market type 1. Thus, it can be seen that all of the demand for fresh pomegranate is met through the produced pomegranate in farms. The different parts of total cost and the different parts of operational cost as the biggest part of the total cost are illustrated in Fig 6. According to the pie chart in Fig 6, the first and the second highest operational costs are the cost of cultivation and import, indicating that the most significant portion of operational costs is related to providing raw materials. The amount of provided pomegranate by import centers and farms to meet the demand of different markets is shown in Fig 7. This chart implies that the model prefers to provide the required pomegranate from farms. Fig 8 illustrates the amount and the percentage of produced pomegranate molasses in each processing and hybrid plant. Finally, Fig 9 shows the amount and percentage of packaged pomegranate molasses in each packaging and hybrid plant. According to Fig 8 and Fig 9, all plants use their full capacity to produce molasses, and hybrid plants 1 and 2 package 75% and 57.2% of their produced molasses, respectively. Hence, the reason for having unmet demand for molasses is the limited capacity of processing and hybrid plants.

6. Sensitivity analyses and managerial implications

6.1. Given weight to objective functions

Decision-makers specify the significance of each objective function by assigning different weights to them. Different weights would affect the solution process and, subsequently, the final results. Three different cases have been defined to observe model sensitivity to these weights. The given weight to each objective function and the obtained outcome from solving the model in each case is mentioned in Table 4 and Fig 10.

In Case 1, when the economic objective is set as the objective with the highest importance, it reaches its highest value among the defined cases. Moreover, this case created the most acceptable balance between sustainability dimensions, where the first objective has its highest value between the cases and the second and third objectives have a value between their best and worst values. In Case 2, the environmental objective function is the most important objective, and all objectives get their lowest value compared to the other two cases. This change is favorable for the environmental objective and unfavorable for the economic and the social objective functions. The depletion in the value of objective functions happens because the model prefers to use cultivation processes with the lowest environmental effects. These cultivation processes have a lower harvesting rate and require fewer workers for the cultivation process, resulting in a reduction in profit and social impacts. Moreover, the model would import pomegranate to make up for the decrease in the pomegranate production in farms due to the change of the cultivation process. In Case 3, the most significant objective function is the social effects. In this case, the model selects the cultivation process that requires the highest number of workers resulting in having the highest social impacts. The selected process requires the highest amounts of fertilizer/manure, pesticide, and water, causing the profit to decrease and environmental effects to increase significantly. Since the selected cultivation process also has the highest harvesting rate of pomegranate, in this case, farms have the largest share in supplying the required pomegranate of the supply chain.

6.2. Sustainability aspects

When decision-makers ignore the social and environmental aspects of their systems, it is clear that the economic objective function gets its best value by breaking all the environmental rules and ignoring all social aspects. The defined problem types in

Table 5 illustrate the impact of each aspect of sustainability on the model.

According to the information in

Table 5 and Fig 11, when only the economic dimension of the network is considered, the economic and environmental objectives get the highest values among defined cases. Based on the nature of these objectives, it is the best case for the economic objective and the worst case for the environmental objective. In the economic problem, the model suggests using cultivation process 20 on 90.5% of farms and the cultivation process 10 on the rest of the farms to increase the harvest rate of pomegranate in farms. Due to the characteristics of these cultivation processes, farms supply 93% of the required pomegranate, and the rest is supplied by import centers. In this case, the environmental objective depletes to its worst value among the problem types. Adding the environmental dimension to the problem persuades the model to choose the cultivation process 9, making all the objectives to get the lowest value among the defined problem types. The harvesting rate of cultivation process 9 is 22.5% lower than cultivation process 20, resulting in a less significant role for farms in supplying the required pomegranate. Finally, solving the sustainable problem to create a balance among sustainability dimensions resulted in the best value for the social effects and a value between the best and worst cases for the environmental and economic objective functions. This balance is created due to the selection of process 10 for pomegranate cultivation in farms.

6.3. Managerial implications

Deciphering the final results and sensitivity analyses would help to present more practical insights. Managerial implications based on the solved problem are outlined as follows.

- According to Fig 5, the biggest portion of earned revenue is attained from selling fresh pomegranate to its specified market. Since most cities of Mazandaran have similar soil and weather, the expansion of farms could be considered by farmers to increase the amount of harvested pomegranate from inside of the network to expand their target market. Moreover, different types of pomegranate trees could be evaluated to investigate the effects of tree types on the harvesting rate of pomegranate. Supply chain managers could consider exporting fresh pomegranate and supply the demand of this market of other provinces to expand their profit.
- The data of Fig 6 determines that the cultivation cost of pomegranate in farms is the highest one in the network. Moreover, it can be implied from the information in the explanation of sensitivity analyses on sustainability dimensions that the selection of the cultivation process significantly influences the social and environmental dimensions of the network. Hence, other types of natural and chemical fertilizers and pesticides and their effects on the harvesting rate and social and environmental aspects should be analyzed and considered for cultivation processes.

Import positively contributes to the environmental and economic objective functions and reduces the amount of unmet demand for pomegranate molasses. The significant role of import can be deduced from the information provided in Table 6. Thus, investigating other provinces and, if possible and reasonable other neighboring countries for importing pomegranate could positively influence environmental and economic aspects. This happens by selecting cultivation processes with lower cultivation costs and less severe environmental impacts and importing the rest of the required pomegranate to meet the market demands.

- The health benefits of pomegranate peel and seeds for humans are explored briefly in the introduction section, and references are provided for more comprehensive studies. Moreover, Fig 4 shows that about 8% of the total revenue of the supply chain is earned from selling pomegranate peel and seeds for preventing them from being wasted. This is when the peel is sold as animal feed, which is not the most beneficial usage due to its numerous health benefits for humans. Other products which are produced from pomegranate peel, would definitely be better decisions for recapturing the value of this product.
- Fig 8 shows that all processing and hybrid plants used their full capacity for producing pomegranate molasses. Moreover, in the results, it is mentioned that market type 1 has 50 tonnes of unmet demand. Hence, increasing the production capacity of these plants could reduce the amount of unmet demand.

7. Conclusion

The developed model aims to maximize the total profit of the chain and the number of job opportunities created due to the selection of cultivation processes and the establishment of potential plants as the economic and social aspects of sustainability. Moreover, to decrease the role of the pomegranate supply chain in greenhouse gas emissions and depletion of renewable freshwater resources, the model aims to minimize the negative environmental aspects by reducing the consumption of fertilizer and pesticide and water used for irrigation in the cultivation processes. The sustainability dimensions are presented as objective functions resulting in having a three-objective optimization model. The IMCGP approach is utilized for addressing the multi-objective model.

The final results proved that the selection of cultivation process significantly affects all aspects of sustainability. According to sensitivity analyses, when all sustainability aspects of the problem are considered, the model creates a balance between sustainability dimensions of the problem by balancing cultivation and import. Moreover, the obtained results indicate that considering sustainability aspects helps the model to perform better, and to decrease the value of the environmental objective function by about 52%, and increase the value of the social objective function by about 17% by a mere 0.2% decrease in the value of the total profit. It is also understood that considering the reverse flow of material and selling pomegranate peel and seeds, which were commonly known as waste, results in gaining 8% of the total revenue of the network, implying their importance. Also, sensitivity analyses illustrate the influence of decision-makers' opinions on the weights of the objective functions, capacity, weather, and import policy changes on optimal decisions.

As future research directions, various types of discounts for providing pomegranate from bigger farms or some specific import centers due to different reasons could be added to the model for extending this research. Variable production and packaging capacity and considering new job opportunities created due to capacity incensement could be taken into account. Export to other provinces or neighboring countries could also be added to the problem. Potential uncertainty in some of the input parameters and addressing the social and environmental aspects of different market types for ranking them could be considered.

References

[1] Li, Z. and Li, J., "The influence mechanism and spatial effect of carbon emission intensity in the agricultural sustainable supply: evidence from china's grain production," *Environmental Science and Pollution Research,* vol. 29, no. 29, pp. 44442-44460, 2022.

[2] Manteghi, Y., Arkat, J., and Mahmoodi, A., "Cooperation mechanisms for a competitive, sustainable food supply chain to reduce greenhouse gas emissions," *Environmental Science and Pollution Research,* vol. 29, no. 21, pp. 32142-32160, 2022.

[3] Gkisakis, V. D., Volakakis, N., Kosmas, E. *et al.*, "Developing a decision support tool for evaluating the environmental performance of olive production in terms of energy use and greenhouse gas emissions," *Sustainable Production and Consumption,* vol. 24, pp. 156-168, 2020.

[4] Moktadir, M. A., Rahman, T., Ali, S. M. *et al.*, "Examining barriers to reverse logistics practices in the leather footwear industry," *Annals of Operations Research,* vol. 293, pp. 715-746, 2020.

[5] Fathollahi-Fard, A. M., Dulebenets, M. A., Tian, G. *et al.*, "Sustainable supply chain network design," *Environmental Science and Pollution Research,* pp. 1-3, 2022.

[6] Magangana, T. P., Makunga, N. P., Fawole, O. A. *et al.*, "Processing factors affecting the phytochemical and nutritional properties of pomegranate (Punica granatum L.) peel waste: A review," *Molecules,* vol. 25, no. 20, p. 4690, 2020.

[7] Kandylis, P. and Kokkinomagoulos, E., "Food applications and potential health benefits of pomegranate and its derivatives," *Foods,* vol. 9, no. 2, p. 122, 2020.

[8] Allaoui, H., Guo, Y., Choudhary, A. *et al.*, "Sustainable agro-food supply chain design using two-stage hybrid multi-objective decision-making approach," *Computers & Operations Research,* vol. 89, pp. 369-384, 2018.

[9] Sazvar, Z., Rahmani, M., and Govindan, K., "A sustainable supply chain for organic, conventional agro-food products: The role of demand substitution, climate change and public health," *Journal of cleaner production,* vol. 194, pp. 564-583, 2018.

[10] Cheraghalipour, A., Paydar, M. M., and Hajiaghaei-Keshteli, M., "A bi-objective optimization for citrus closed-loop supply chain using Pareto-based algorithms," *Applied Soft Computing,* vol. 69, pp. 33-59, 2018.

[11] Banasik, A., Kanellopoulos, A., Bloemhof-Ruwaard, J. M. *et al.*, "Accounting for uncertainty in eco-efficient agri-food supply chains: A case study for mushroom production planning," *Journal of cleaner production,* vol. 216, pp. 249-256, 2019.

[12] Roghanian, E. and Cheraghalipour, A., "Addressing a set of meta-heuristics to solve a multi-objective model for closed-loop citrus supply chain considering CO2 emissions," *Journal of cleaner production,* vol. 239, p. 118081, 2019.

[13] Hosseini-Motlagh, S.-M., Samani, M. R. G., and Abbasi Saadi, F., "Strategic optimization of wheat supply chain network under uncertainty: a real case study," *Operational research,* vol. 21, pp. 1487-1527, 2021.

[14] Cheraghalipour, A., Paydar, M. M., and Hajiaghaei-Keshteli, M., "Designing and solving a bi-level model for rice supply chain using the evolutionary algorithms," *Computers and Electronics in Agriculture,* vol. 162, pp. 651-668, 2019.

[15] Mogale, D., Cheikhrouhou, N., and Tiwari, M. K., "Modelling of sustainable food grain supply chain distribution system: a bi-objective approach," *International Journal of Production Research,* vol. 58, no. 18, pp. 5521-5544, 2020.

[16] Jabarzadeh, Y., Reyhani Yamchi, H., Kumar, V. *et al.*, "A multi-objective mixed-integer linear model for sustainable fruit closed-loop supply chain network," *Management of Environmental Quality: An International Journal,* vol. 31, no. 5, pp. 1351-1373, 2020.

[17] Motevalli-Taher, F., Paydar, M. M., and Emami, S., "Wheat sustainable supply chain network design with forecasted demand by simulation," *Computers and Electronics in Agriculture,* vol. 178, p. 105763, 2020.

[18] Chavez, M. M. M., Sarache, W., Costa, Y. *et al.*, "Multiobjective stochastic scheduling of upstream operations in a sustainable sugarcane supply chain," *Journal of Cleaner Production,* vol. 276, p. 123305, 2020.

[19] Liao, Y., Kaviyani-Charati, M., Hajiaghaei-Keshteli, M. *et al.*, "Designing a closed-loop supply chain network for citrus fruits crates considering environmental and economic issues," *Journal of Manufacturing Systems,* vol. 55, pp. 199-220, 2020.

[20] Hosseini-Motlagh, S.-M., Samani, M. R. G., and Saadi, F. A., "A novel hybrid approach for synchronized development of sustainability and resiliency in the wheat network," *Computers and electronics in agriculture,* vol. 168, p. 105095, 2020.

[21] Mogale, D., Ghadge, A., Kumar, S. K. *et al.*, "Modelling supply chain network for procurement of food grains in India," *International Journal of Production Research,* vol. 58, no. 21, pp. 6493-6512, 2020.
[22] Keshavarz-Ghorbani, F. and Pasandideh, S. H. R., "A Lagrangian relaxation algorithm for optimizing a bi-objective agro-supply chain model considering CO2 emissions," *Annals of Operations Research,* vol. 314, no. 2, pp. 497-527, 2022.
[23] Kazemi, M. J., Paydar, M. M., and Safaei, A. S., "Designing a bi-objective rice supply chain considering environmental impacts under uncertainty," *Scientia Iranica*, 2021.
[24] Salehi-Amiri, A., Zahedi, A., Akbapour, N. *et al.*, "Designing a sustainable closed-loop supply chain network for walnut industry," *Renewable and Sustainable Energy Reviews,* vol. 141, p. 110821, 2021.
[25] Jamali, A., Ranjbar, A., Heydari, J. *et al.*, "A multi-objective stochastic programming model to configure a sustainable humanitarian logistics considering deprivation cost and patient severity," *Annals of operations research,* pp. 1-36, 2021.
[26] Chang, C.-T., "Multi-choice goal programming," *Omega,* vol. 35, no. 4, pp. 389-396, 2007.
[27] Jadidi, O., Cavalieri, S., and Zolfaghari, S., "An improved multi-choice goal programming approach for supplier selection problems," *Applied mathematical modelling,* vol. 39, no. 14, pp. 4213-4222, 2015.

List of figures

List of tables

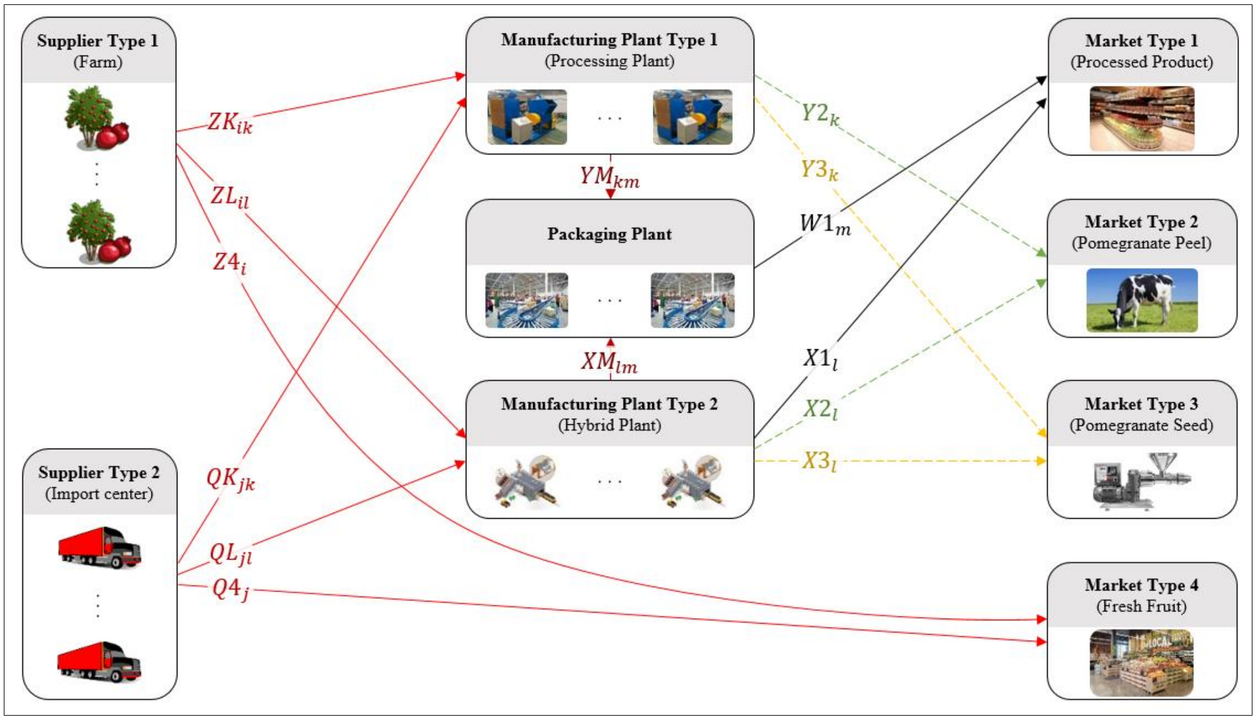

Fig 1. The structure of the addressed network

Cultivation process	1	2	3	4	5	6	7	8	9	10
Manure	–	–	–	–	%50	%50	%50	%50	%100	%100
Pesticide	–	–	✓	✓	–	–	✓	✓	–	–
Irrigation	–	✓	–	✓	–	✓	–	✓	–	✓

Cultivation process	11	12	13	14	15	16	17	18	19	20
Manure/Chemical fertilizer	%100	%100	%50	%50	%50	%50	%100	%100	%100	%100
Pesticide	✓	✓	–	–	✓	✓	–	–	✓	✓
Irrigation	–	✓	–	✓	–	✓	–	✓	–	✓

Manure	Chemical fertilizer	Pesticide	Water
100%=10 (tonne/hectare)	100%=0.3 (tonne/hectare)	15 (liter/hectare)	90000 (liter/hectare)

Fig 2. Details of the cultivation processes

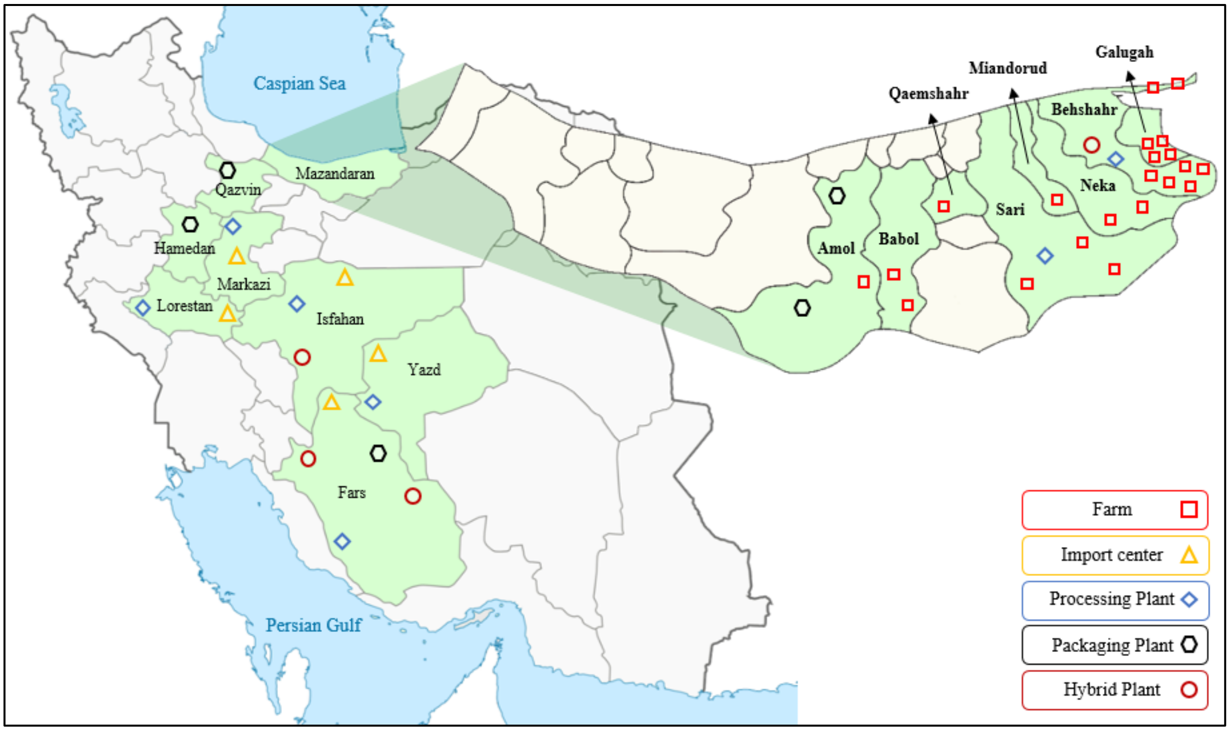

Fig 3. Location of the facilities of the considered case

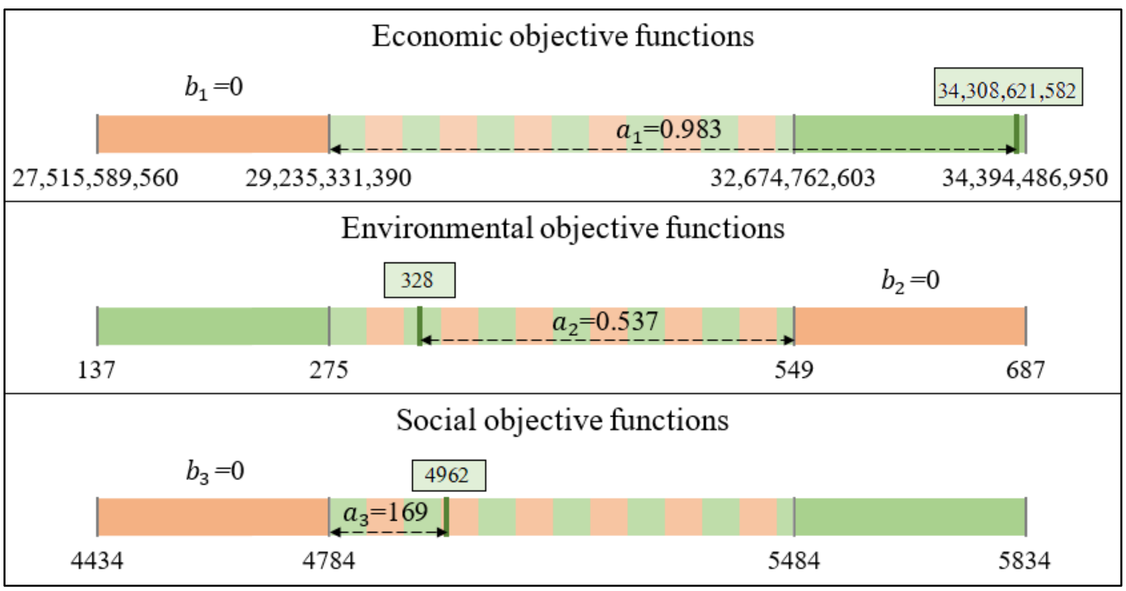

Fig 4. Value of each objective function and variables of IMCGP approach

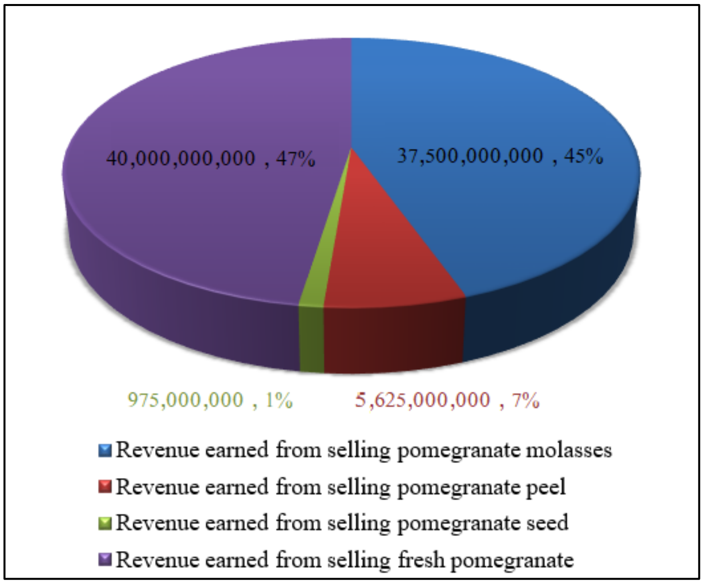

Fig 5. Details of earned revenue

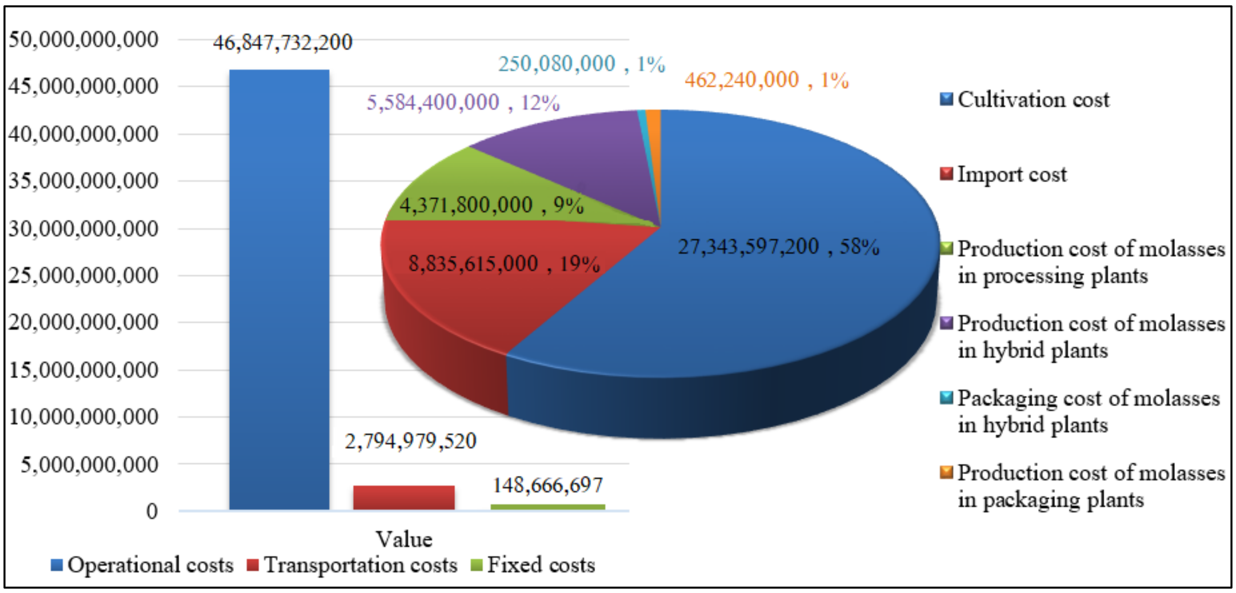

Fig 6. Details of total costs and operational costs

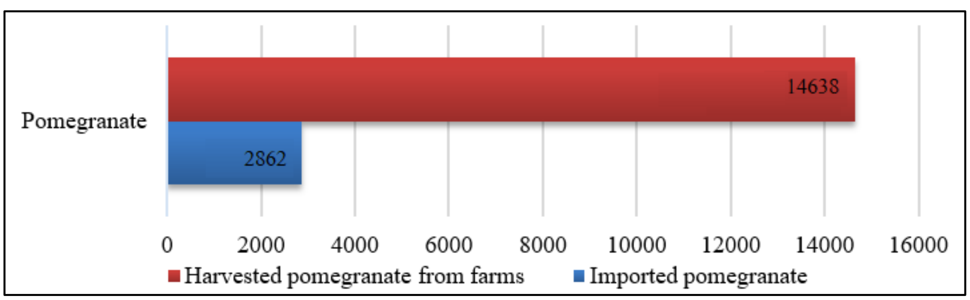

Fig 7. Provided pomegranate by each supplier type

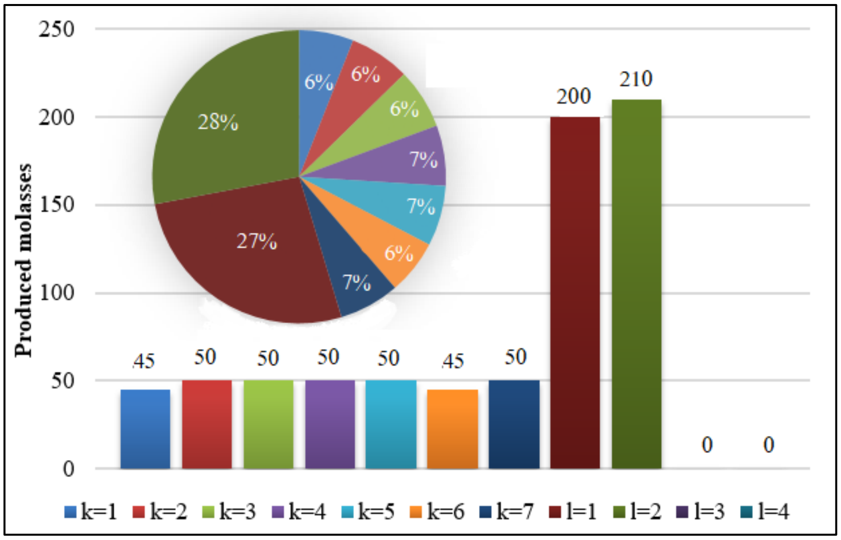

Fig 8. Details of molasses produced by processing and hybrid plants

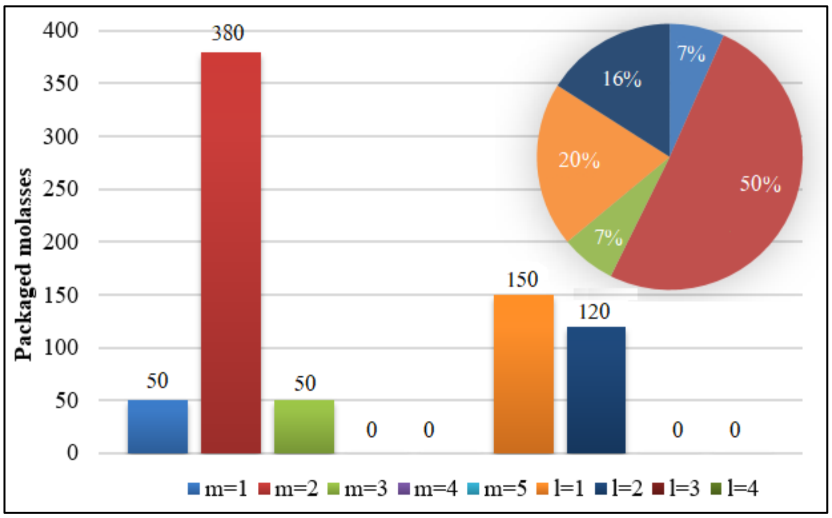

Fig 9. Details of molasses packaged by processing and hybrid plants

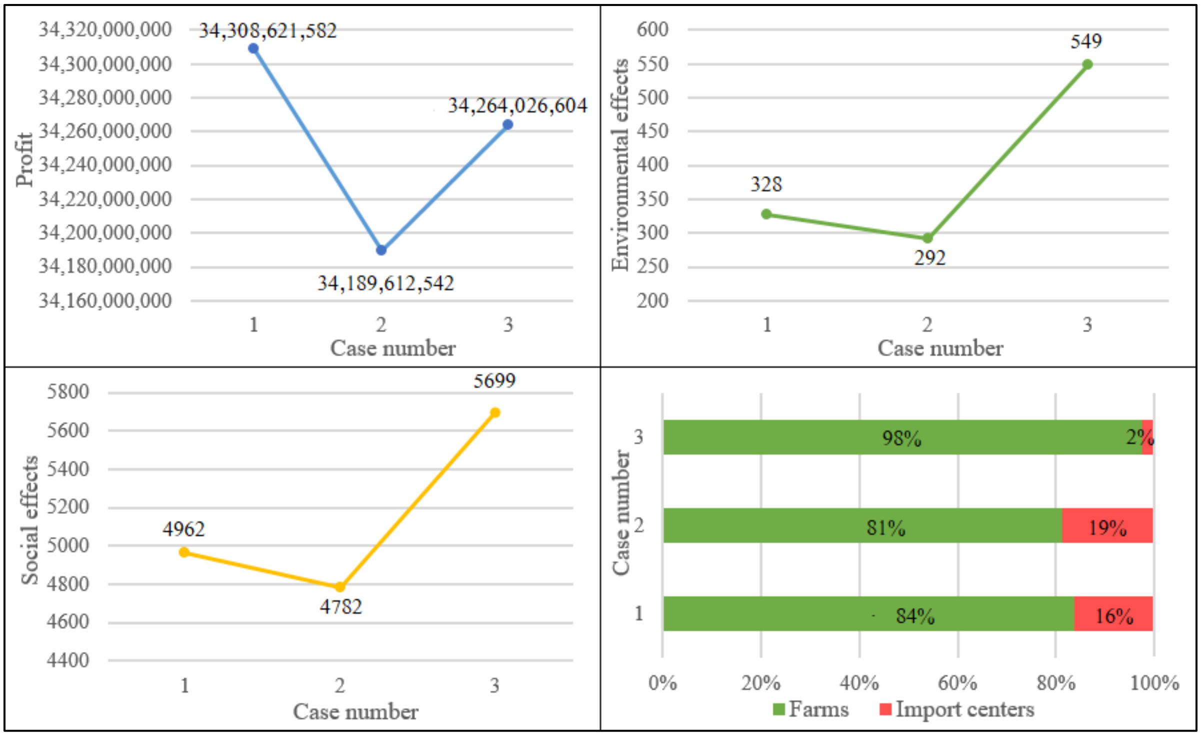

Fig 10. Details of the results for weight change analysis

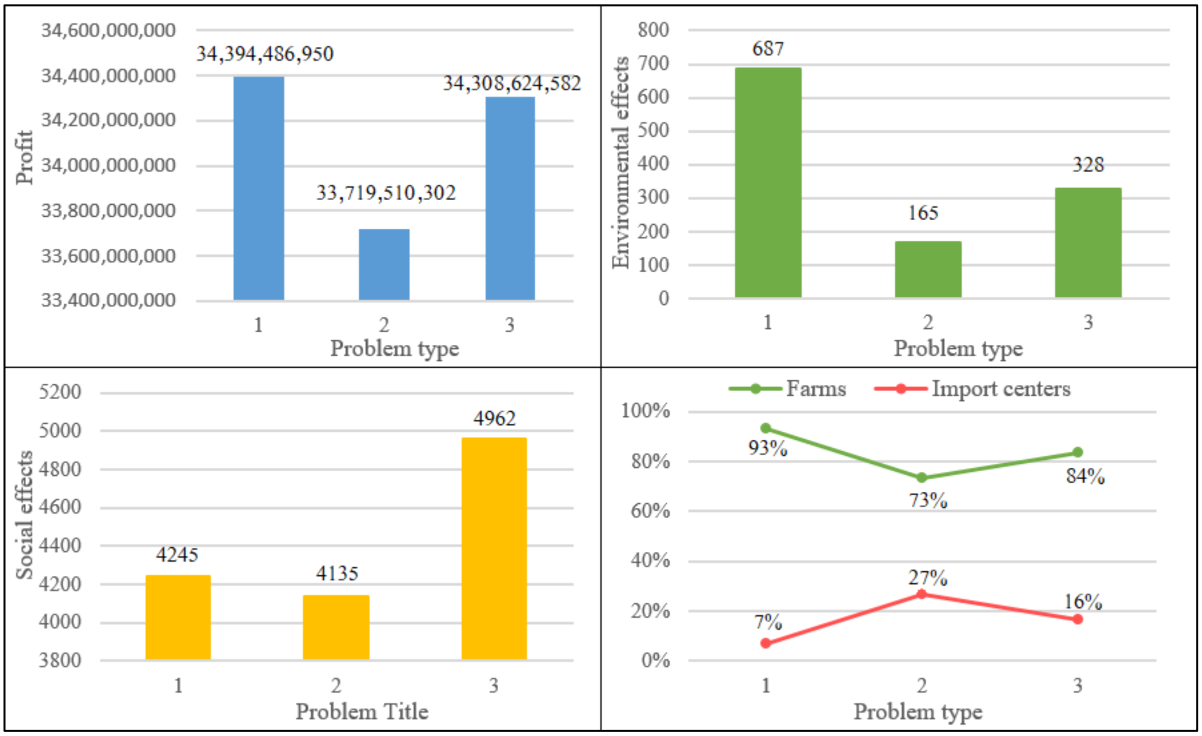

Fig 11. Details of the results for sustainability aspects analysis

Table 1. Value of indices

Index	Description	Value
o	Cultivation process	20
i	Farm	21
j	Import center	5
k	Processing plant	7
l	Hybrid plant	4
m	Packaging plant	5

Table 2. The upper and lower bound of objective functions and their given weight

Objective function (u)	Economic (1)	Environmental (2)	Social (3)
go_u^+	34,394,486,950	137	5834
$go_{u,max}$	32,674,762,603	549	5484
$go_{u,min}$	29,235,331,390	275	4784
go_u^-	27,515,589,560	687	4434
wa_u=wb_u	0.6	0.3	0.1

Table 3. Details of the environmental objective function

Item	Manure/Chemical fertilizer	Pesticide	Water
Value	8270 (Tonnes)	0 (Liters)	48,843,975 (Liters)

Table 4. Results of weight variation

Case	wa_1= wb_1	wa_2= wb_2	wa_3= wb_3	Objective Function			Production	Import
				Economic	Environmental	Social		
1	**0.6**	**0.3**	**0.1**	**34308621582**	**328**	**4962**	**14638**	**2862**
2	0.3	0.6	0.1	34189612542	292	4782	14242	3258
3	0.1	0.3	0.6	34264026604	549	5699	17070	430

Table 5. Results of considering sustainability aspects

Problem Type	Objective Function			Production	Import
	Economic	Environmental	Social		
Economic	34394486950	687	4245	16540	1213
Green	33719510302	165	4135	12819	4682
Sustainable	**34308621582**	**328**	**4962**	**14638**	**2862**

Table 6. Details of import policy change analysis

Case	Objective Function			Unmet Demand
	Economic	Environmental	Social	
Import available	**34308621582**	**328**	**4962**	**50**
Import not available	33866196404	549	5699	93

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Technical biography of authors

Mohammad Pourmehdi is an Engineering Doctorate (EngD) candidate in Business and Information Technology at the University of Twente, Enschede, the Netherlands. He graduated with BSc and MSc in Industrial Engineering from Babol Noshirvani University of Technology, Babol, Iran, in 2017 and 2019, respectively. His research interests are Logistics and Supply Chain Management Business and IT Collaboration, Applied Operations Research, and Industry 4.0.

Seyed Hossein Hosseinian-Kashani obtained his B.Sc. & M.Sc. degrees in industrial engineering from the Babol Noshirvani University of Technology, Babol, Iran in 2017 & 2021, respectively. Currently, he is employed at the Babol Noshirvani University of Technology Incubator. His research interests revolve around supply chain management, productivity enhancement, and feasibility studies.

Mohammad Mahdi Paydar is an Associate Professor of Industrial Engineering at the Babol Noshirvani University of Technology, in Babol, Iran. He received his BS and MS degrees in Industrial Engineering from Mazandaran University of Science and Technology, Babol, Iran, in 2007 and 2009, respectively; and PhD degree in Industrial Engineering from Iran University of Science and Technology in 2014. His research interests include supply chain design, applied operations research, multi-objective optimization, and cellular manufacturing. He has published more than 90 papers in well-known international journals.

Ali Divsalar is an assistant professor at the department of industrial engineering at Babol Noshirvani University of Technology, Iran. He received his PhD in industrial engineering from KULeuven in Belgium and has since focused his research on using advanced data analytics and operations research techniques to solve logistics and supply chain management problems. His specific research interests include Prescriptive analytics, optimization, and applied operations research. He has published numerous research papers in top international journals, including European Journal of Operational Research, Computers & Operations Research, International Journal of Production Economics, Expert Systems with Applications, and Applied Soft Computing.