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Sustainable fuel supply network design by integrating gas oil and biodiesel supply chains under uncertainty

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Abstract

In recent years, research has shown that biomass as an alternative energy source for fossil fuels can be effective in decreasing recent environmental crises. Next, the researchers examined how biofuels are produced through the oil supply chain infrastructure and came up with useful results. This paper is the first study to present the decisions of both chains simultaneously through a mathematical optimization model for the gas oil and biodiesel supply chains. The model proposed in this paper determines the connection point of two chains and other decisions related to network design with a sustainable development approach. The method used in this paper for solving the multi-objective model is the augmented epsilon constraint method. Also, to consider the uncertainty in export demand, the two-stage scenario-based stochastic programming method has been used. Finally, the performance of the mathematical programming model has been investigated through a case study in Iran, and its sensitivity analyzes have been performed.

Keywords: Gas-oil supply chain, bioenergy supply chain, optimization, sustainability, uncertainty

1- Introduction

The current global energy consumption shows a significant ascending trend until 2030. Increasing pollution and environmental concerns, declining fossil fuels, climate change, crises in international relations, and fuel price fluctuations have led to serious challenges for energy supply planning and management (Ghelichi et al., 2018). In recent years, on the one hand, issues such as energy security and countries' dependence on fossil fuels, and on the other hand, environmental pollution crises, have led countries to alternative sources that eliminated these two challenges. Experts have examined alternative sources which are renewable and cleaner than the others. By considering that the transportation sector has a great impact on environmental pollution, finding alternative sources in this sector can help reduce environmental pollution. Experts believe that using clean energy such as solar energy, wind, geothermal, biomass, etc. instead of fossil fuels' energy will prevent environmental pollution and its dangers (Ward et al., 2017). Expert research in this regard shows that given biofuels can be supplied from a variety of such sources and can be economically and environmentally suitable alternative sources for fossil fuels (Atabani et al., 2014). Biofuels can be produced from biomass, including waste from some agricultural, household, commercial and industrial products, cultivation of some agricultural products, and so on. Bioethanol and biodiesel as liquid biofuels can be used as direct fuels for vehicles or in combination with oil-based fuels (Ghadami et al., 2021). Biodiesel is a type of biofuel that can be successfully used with gas oil obtained from fossil fuels and combined in different percentages for use in transportations of vehicles (Peri and Baldi, 2013).

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Jatropha plant is a promising source for biodiesel production that has been considered by many researchers due to its high oil content, drought tolerance, and water scarcity, soil reclamation, desert reduction, rural development, and environmental benefits (Achten et al., 2008).

The issue of designing the oil Supply chain network and its derivatives, as well as biofuels, has been considered by many researchers due to its various strategic, tactical and operational decisions. The answer to all decisions of location, allocation, capacity determination, capacity expansion, technology selection, production planning, inventory management, etc. can be provided in the form of a supply chain network design model. In recent years, articles have examined the supply chain of oil and petroleum products as well as biofuels in order to make energy supply decisions optimally. In articles related to the supply chain of oil and oil products, part or all of the supply chain is optimally integrated. In articles related to biofuels, supply chain optimization is considered by considering one of the generations of biomass as a feedstock.

In recent years, researchers have examined the integration of the biofuel supply chain with the infrastructure of production and distribution of the oil supply chain and have shown three connection points for these two chains. First, after pre-processing the biomass, it is combined with crude oil and goes to distillation towers. Second, the semi-finished material goes to the upgrading units for further processing, and third, the finished fuel goes to the storage or distribution site of the final product to use the existing distribution capacity.

This eliminates the need to build many facilities in the biofuel supply chain and reduces many costs. Therefore, in some articles, they study how this integration and techniques of converting biomass into biofuels through the infrastructure of existing oil refineries. They concluded that there are three techniques for doing this: catalytic cracking, hydrocracking, and hydrotreating (Huber and Corma, 2007). In order to reduce the cost of biofuels and reach a competitive level with fossil fuels, an advanced supply chain model that considers network design, logistics, and network planning decisions to take advantage of existing oil refinery infrastructure is essential (Tong et al., 2013).

In this paper, a multi-objective stochastic mixed-integer linear programming model is proposed to design an integrated biodiesel and gas oil supply chain. The proposed model considers all parts of both chains from harvesting centers in the biodiesel supply chain and oil fields in the gas oil supply chain to final customers. In addition to maximizing profits as an economic goal, the proposed model considers minimizing carbon dioxide emissions as an environmental goal and maximizing the social aspects as a social goal. Jatropha plant is considered as a feedstock in the biodiesel supply chain due to its suitable properties for biodiesel production. This model is used in various strategic and tactical decisions such as location, allocation, capacity expansion, production planning, and inventory management. This article is used for a real case in Iran for the 20-year planning horizon.

The uncertain parameters in this study are "crude oil export demand" and "product export demand". The reason for the uncertainty of these parameters is the international relations, the imposition of sanctions, and the activities that may occur differently in each year depending on the type of foreign policy. In this regard, in this study, a two-stage scenario-based stochastic approach is used. In this method, variables such as binary variables that are strategic and not dependent on scenarios can be determined in the first stage and other variables can be changed in each period according to the scenario as known as second stage variables.

In the following and the second part, the literature review of articles on the oil and biofuels supply chain are discussed separately. In the third part, the problem under study is described and the related mathematical modeling is presented. In the fourth part, the solution approach used in the article is examined. In the fifth section, the case study is reviewed and its results are analyzed, and at the end of the chapter, the validity of the research model is performed. Finally, in the sixth chapter, the results and suggestions for future research are presented.

2- Literature review

In order to better understand the studies conducted on the supply chain of oil and its derivatives, as well as the supply chain of biofuels, in this section, articles and studies performed on these two supply chains are reviewed separately.

2-1- Literature review of petroleum supply chain

The structure of the oil supply chain and its derivatives includes the upstream segment, including oil fields and crude oil storage centers, the midstream segment, such as refineries and petrochemicals, and product storage centers, and the downstream segment, such as distribution centers and different kinds of customers. Much research has been done on the downstream and midstream parts of the oil supply chain. In 2013, Fernandez et al. envisioned a multi-level, multi-product, multi-transportation mode downstream oil supply chain network (Fernandes et al., 2013). In 2021, Lima et al. presented a mixed-integer linear programming model to design a downstream oil supply chain. Their MILP model aims at determining the network design and the products distribution plan in a cost-effective way (Lima et al., 2021). In 2015, Kazemi et al. proposed a mixed-integer linear programming model for multi-product and multi-level costs downstream oil supply chain network that minimizes the costs (Kazemi and Szmerekovsky, 2015). In 2020, Wang et al. developed to support the decisions of the distribution plan in the supply chain. Their method is handy for analysis under non-standard conditions, such as transport facility disruption and demand increase (Wang et al., 2020). Their model deals with multi-modal transportation planning in strategic supply chain design. In 2015, Ghaffarpour et al. Designed the downstream part of the oil supply chain. They showed a hierarchical structure, including a mathematical optimization model for determining strategic decisions in the leader problem and a simulation model for determining tactical and operational decisions in a follower problem (Ghezavati et al., 2015). In 2016, Ozturkoglu et al. developed a deterministic single-period, single-product mathematical model and analyzed scenarios such as failures in pipeline connections (Öztürkoğlu and Lawal, 2016). In 2018, Lima et al. presented multi-stage stochastic programming to optimally solve the refined product problems (Lima et al., 2018).

Some researchers have studied the upstream oil supply chain or all parts of the integrated supply chain. In 2013, Liras et al. examined the issue of integration and coordination under uncertainty at the tactical and operational levels (Leiras et al., 2013). In 2014, Sahebi et al. proposed a multi-objective mathematical model with environmental considerations for the upstream oil supply chain. Supply chain network design, technology selection, pipeline network construction, and oil tanker planning are specified in this model (Sahebi et al., 2014). In 2016, Moradi Nasab et al., In a study, presented an integrated multi-period, multi-stage and multi- transportation mode oil supply chain model to obtain an optimal global solution. They considered both construction and increasing capacity of the facility and the pipeline route at the same time (Nasab and Amin-Naseri, 2016). In 2017, Farahani et al. introduced a mixed integer linear programming model to maximize the net present value of a crude oil network. The effect of gas injection and swap at the same time is creatively considered in their proposed model (Farahani and Rahmani, 2017). In 2017, Azadeh et al. presented a multi-objective mathematical model for integrating the up and midstream sections of the crude oil supply chain, by considering environmental indicators. In this paper, an algorithm based on the decomposition approach is used to solve the proposed model (Farahani and Rahmani, 2017).

Decision levels can vary between articles. The most important decisions can be location, capacity determination, technology selection, allocation, production planning, inventory management, and transportation-related decisions. In 2013, Fernandez et al., with the help of deterministic mixed integer linear programming strategically designed and programmed the downstream network of the oil supply chain and determined the optimal location of storage centers, optimal capacities, and transportation modes for long-term programming. This MILP model maximizes total profits for oil companies during the supply, refining, distribution, and retail stages and has been tested with a real oil supply chain network in Portugal (Fernandes et al., 2013).

In terms of modeling, articles can be classified in different ways. The most common types are Linear programming, mixed integer linear programming, nonlinear programming, nonlinear mixed integer programming. Articles can also be divided into single-objective and multi-objective in terms of the objective function. Many multi-objective models in this field consider economic and environmental functions. In 2020, Zhou et al. proposed a multi-objective mixed-integer linear programming model to minimize total economic costs and carbon dioxide emissions simultaneously (Zhou et al., 2020). Uncertainty in the parameters is another important point that should be considered in the classification of articles. The uncertainty approach in articles can be classified into three categories: fuzzy, robust, and stochastic. In 2014, Oliveira et al. proposed a two-stage stochastic programming model for the oil supply chain. They also used the development of the stochastic benders decomposition method to solve it (Oliveira et al., 2014). In 2014, Gupta et al. presented a multi-stage stochastic model for offshore oil and gas field infrastructure programming (Gupta and Grossmann, 2014).

2-2- Literature review of biofuel supply chain

The structure of the supply chain network considered in many articles in this field is similar and in some cases slightly different. The feedstock considered in biofuel supply chain articles can be different. Most articles consider second-generation feedstock. Some articles also consider a combination of generations. In 2016, Babazadeh introduced a multi-product and multi-period biodiesel supply chain network design model. He used Jatropha seeds and waste edible oil to produce second-generation biodiesel (Babazadeh, 2017). In 2017, Babazadeh et al**.** presented a possible multi-objective programming model for designing a second generation biodiesel supply chain network under risk conditions. This paper presents a planning method for risk reduction based on possible uncertainty (Babazadeh et al., 2017). In 2018, Ezzati et al. designed a biodiesel supply chain network, considering Jatropha, waste oil, and microalgae as feedstock. They presented a multi-period, multi-product, and multi-transportation mode mixed integer linear programming model that integrates all levels of the chain (Ezzati et al., 2018). In 2020, Mahjoub et al. developed a multi-objective mixed integer linear programming model that designs a second/third generation biofuel supply chain. They studied three types of biomass simultaneously as raw materials for production and used the augmented epsilon constraint method to solve it (Mahjoub et al., 2020). In 2020, Kang et al. proposed a three-step model for designing a biofuel supply chain from microalgae. The first stage is the design of economic decisions and analyzes, the second stage is the selection of candidate locations based on GIS and the third stage is mathematical optimization (Kang et al., 2020). Rabani et al. developed a new optimization model using mixed integer linear programming with the objective of maximizing the total profits of biodiesel supply chain incorporating environmental and social costs (Rabani et al., 2020). Biofuel articles can help you make decisions at different levels. In 2014, Lin et al. proposed a mixed integer linear programming model for optimizing strategic and tactical decisions. This model covers all activities from harvesting to distribution (Lin et al., 2014). In some articles, issues such as the seasonality of the feedstock have been considered in the design of the biofuel supply chain network. In 2013, Xie et al. proposed a multi-stage mixed-integer linear programming model for the cellulosic biofuel supply chain. This article examines the seasonality of biomass (Xie et al., 2014).

Biofuel supply chain articles can also be single-objective or multi-objective. The objectives of these articles can be mainly economic, environmental and social. Ahranjani et al. (2018) present a model that simultaneously considers economic, environmental, and social goals (Mousavi Ahranjani et al., 2018). In 2018, Fattahi et al. considered environmental effects, and social aspects in their model (Fattahi and Govindan, 2018). In 2021, Habib et al. designed an animal fat-based biodiesel supply chain network to optimize economic and environmental goals. Their model minimizes the total cost of biodiesel supply chain besides minimizing the carbon emissions (Habib et al., 2021). Saravi et al. presents a novel approach based on Z-number data envelopment analysis (DEA) model to handle severe uncertainty associated with actual data. Their multi-objective mathematical model considers environmental, economic and social aspects of biomass plants (Akbarian Saravi et al., 2018). In 2021, Mohtashami et al. presented a two-stage approach. In the first stage, they specifies candidate locations for biomass cultivation with a common weight data envelopment analysis (CWDEA) method. In the second stage, strategic and tactical decisions were made by a mathematical model (Mohtashami et al., 2021)**.** In 2018, Abdul Ghani et al. studied the impact of incentives, on the one hand, and greenhouse gas emission offenses on the other, so the farmers avoid burning biomass feedstock residues and provide opportunities to convert these materials into biofuels. As a result, the costs and the emission of greenhouses gases are reduced (Ghani et al., 2018). Bairamzadeh et al. maximized the efficiency objective function for designing and programming the biofuel supply chain, and in addition to the physical flow, they also considered the optimization of the financial flow (Bairamzadeh et al., 2018).

Another feature of articles in this field is the certainty or uncertainty of network design. Articles that consider uncertainty in parameters are generally classified into three categories: fuzzy, robust, and stochastic. In 2016, Zhang et al. designed a biofuel supply chain based on waste cooking oil at strategic and tactical levels. They presented a multi-objective mixed integer programming model with a robust approach (Zhang and Jiang, 2017). In 2016, Mohseni et al. presented a two-stage model for designing and planning a microalgae biodiesel supply chain. They used GIS and AHP to identify potential locations. They used a mixed integer linear programming model to optimize under uncertainty . In 2017, Bairamzadeh et al. presented a mixed integer linear programming model to determine the strategic and tactical decisions of the lignocellulosic bioethanol supply chain. A hybrid robust optimization model has been used to consider the uncertainties (Bairamzadeh et al., 2018). In 2018, Qelichi et al. presented a two-stage stochastic programming model for designing an integrated biodiesel green supply chain network from Jatropha seeds. In their multi-product and multi-period mixed integer linear programming model, they developed a two-stage scenario-based stochastic programming method (Ghelichi et al., 2018). In 2018, Fattahi et al. presented a multi-stage stochastic programming model for the design and planning of the biofuel supply chain (Fattahi and Govindan, 2018). In 2018, Ghaderi et al. presented a multi-objective possibility robust programming model for designing a bioethanol sustainable supply chain network (Ghaderi et al., 2018). In 2019, Babazadeh et al. presented a possibilistic programming model for the design of the second generation biodiesel supply chain network under uncertainty. Jatropha and waste cooking oils are considered as the feedstock of biodiesel. They also used benders local branching algorithm to solve their model (Babazadeh et al., 2019). In 2019, Razm et al. redesigned the biomass supply network, considering price changes as a decision variable. They examined the rate of change in price and demand in three different scenarios (Razm et al., 2019).

None of the above articles have considered the use of oil network infrastructure for biofuel production. In 2013, Tong et al. optimally designed and strategically planned an integrated biofuel system and oil supply chain under uncertainty. In this paper, a two-stage stochastic mixed integer linear programming model is proposed for optimal design and integrated strategic programming of hydrocarbon and petroleum fuels under uncertainty (Tong et al., 2013). In 2014, Tung et al. optimized the design of an advanced hydrocarbon biofuel supply chain integrated with existing oil refineries and analyzed three biofuel supply chain connection point with oil refineries. They also provided a multi period fuzz MILP model to consider uncertainties (Tong et al., 2014a). Also Tong et al. (2014) in another paper, discuss the optimal design of an advanced hydrocarbon biofuel supply chain integrated with existing oil refineries and using a robust optimization approach, determine the integration strategy (Tong et al., 2014b).

2-3- Contributions of this paper

Therefore, the contributions of this study are briefly as follows:

- Integrating gas oil and biodiesel supply chain network simultaneously.
- Considering a comprehensive (upstream, midstream, and downstream) gas oil supply chain and integrated design for each of the two chains.
- Formulating the multi-objective function for economic, environmental, and social optimization of supply chain.
- Simultaneous studying of environmental pollution caused by transportation within the supply chain and reduction of pollution due to the use of biodiesel instead of diesel.
- Considering the migration to metropolises and border cities, unemployment rate and number of jobs created as social factors.
- Solving the proposed model for a real case study in Iran and analysing the results.

3- Problem definition and mathematical formulation

The issue discussed in this study is the design of an integrated gas oil and biodiesel supply chain network, which considers all parts of both chains from harvesting centers in the biodiesel supply chain and oil fields in the gas oil supply chain to final customers. The issue discussed in this study is investigated through a multi-objective model in order to optimize economic, environmental, and social goals as the elements of sustainable development.

Crude oil enters the crude oil storage centers from the oil fields, which some parts of them are exported. In the biodiesel supply chain, Jatropha can also be transferred from harvesting centers to storage centers and then to preprocessing centers and bio-refineries. On the other hand, in the biodiesel supply chain, after bioslurry pre-processing, enters the crude oil storage centers. The inflows to the crude oil storage centers, enter the distillation towers. In distillation towers, gas oil is obtained after separation and this diesel cannot be used by the consumer according to the standards and must be processed in the final production units. In the pre-processing units, bioslurry and bio-oil were obtained, that the bio-oils enter directly into the upgrading units in the oil refineries. On the other hand, materials that come out of pre-processing units can be turned into the final product in the upgrading units in the biofuel chain. Also, from biomass collection centers, Jatropha can be transferred directly to bio-refineries and all processes can be done there and the final product can be obtained. The final product obtained from the upgrading units in the oil supply chain enters the product storage centers as well as the production units. There are two ways for the final products obtained from bio-refineries and upgrading centers in the biofuel supply chain: either to enter the storage centers of the products and after mixing and then, sent to distribution centers or to be sent directly to distribution centers and mixed there. It is sent from distribution centers to customer centers, industry and, export centers. Figure 1 shows a schematic of the network examined in this paper**.**

Oil fields, crude oil storage centers, distillation towers, upgrading units in the gas oil supply chain, refinery production units, product storage centers, export terminals, distribution centers, Jatropha harvesting sites, Jatropha collection centers, pre-processing units, upgrading units in the biodiesel supply chain and biorefinery have a certain capacity level. Except for production units in the refinery, other items have a fixed capacity. Production units in the refinery can increase capacity to a certain extent. Infinite capacity is provided for vehicles and only one mode of transport is considered. The model will determine the construction upgrading units in the gas oil supply chain, Jatropha harvesting sites, Jatropha collection centers, pre-processing units, upgrading units in the biodiesel supply chain, bio-refineries and, distribution centers. Inventory costs are considered for crude oil storage centers, product storage centers, and Jatropha collection centers. In upgrading units in the gas oil supply chain, production units in the refinery, pre-processing units, upgrading units in the biodiesel supply chain, and bio-refineries, production efficiency is considered. The issue is for a time horizon of 20 years and is considered as a period time each year. The main decisions made by the model are location, allocation, capacity expansion, inventory management and production planning. This section presents a mathematical model for designing and optimizing the supply chain network in figure 1. First, the symbols used in modeling are introduced. The corresponding mathematical model will then be presented.

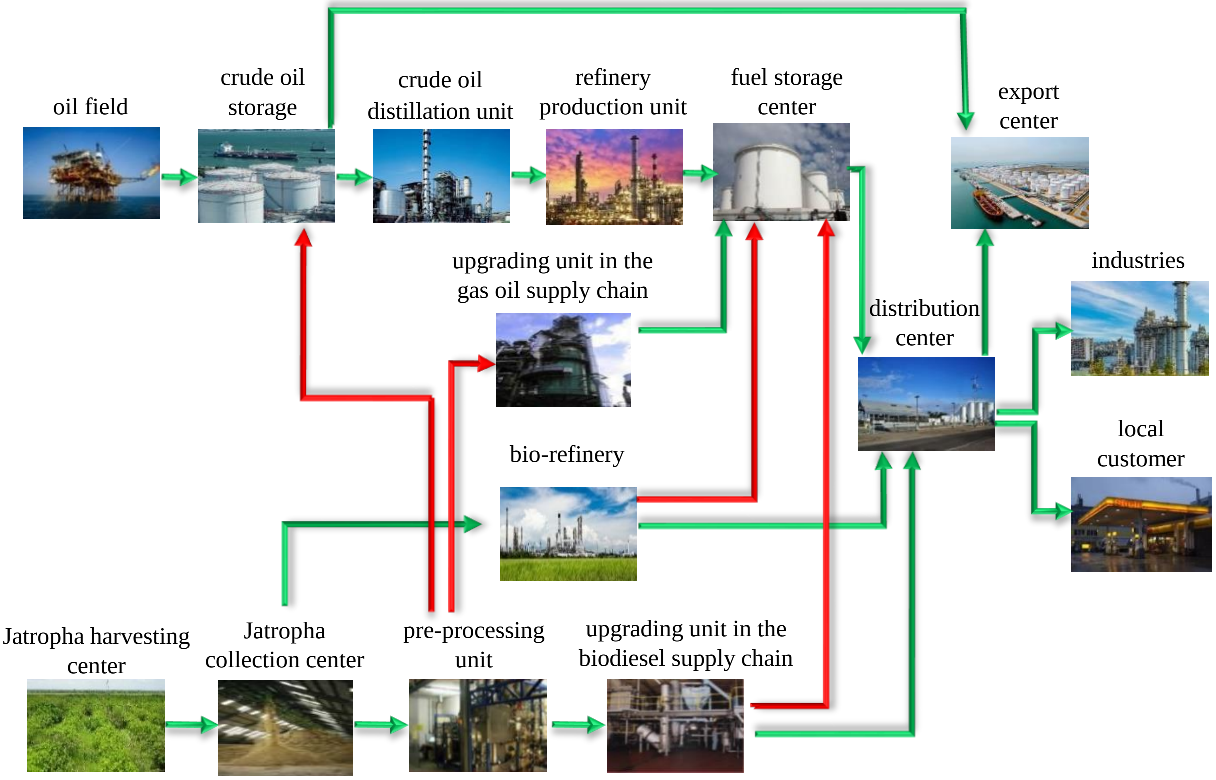

Fig. 1. The structure of the integrated gas oil and biodiesel supply chain network studied in this paper

3-1- Notations

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

Indices	
of	Index of locations for oil fields
so	Index of locations for crude oil storage
du	Index of locations for crude oil distillation centers
pu	Index of locations for refinery production units
uu	Index of locations for upgrading units in the gas oil supply chain
s	Index of locations for fuel storage centers
ex	Index of locations for export centers
cu	Index of locations for customers
in	Index of locations for industries
dc	Index of locations for distribution centers
h	Index of locations for Jatropha harvesting centers
c	Index of locations for Jatropha collection centers
p	Index of locations for pre-processing units
u	Index of locations for upgrading units in the biodiesel supply chain
br	Index of locations for bio-refineries
t	Index of time periods
se	Index of scenario

Parameters	
cc_t^{uu}	Cost of construction upgrading unit uu in gas oil supply chain in period t ($).
cc_t^{pu}	Cost of expanding a unit capacity of refinery production unit pu in the gas oil supply chain in the period t ($).
cc_t^{h}	Cost of purchasing a unit of the capacity of the Jatropha harvesting center h in period t ($).
cc_t^{c}	Cost of constructing the Jatropha collection center c in period t ($).
cc_t^{p}	Cost of constructing pre-processing unit p in period t ($).
cc_t^{dc}	Cost of construction distribution center dc in period t ($).
cc_t^{u}	Cost of constructing upgrading unit u in biodisel supply chain in period t ($).
cc_t^{br}	Cost of construction bio-refinery br in period t ($).
dpr_t^{cu}	Demand of customer cu of fuel in period t (barrel).
dpr_t^{in}	Demand of industry in of fuel in period t (barrel).
$dpr_{se,t}^{ex}$	Demand of export terminal ex of fuel in period t for scenario se (barrel).
$dco_{se,t}^{ex}$	Demand of export terminal ex of crude oil in period t for scenario se (barrel).
ca_{of}	Maximum capacity of oil field processing of (barrel).
ca_{so}	Maximum capacity of crude oil storage so (barrel).
ca_{du}	Maximum capacity of distillation unit du (barrel).
ca_{uu}	Maximum capacity of upgrading unit uu in gas oil supply chain (barrel).
ca_{s}	Maximum capacity of fuel storage s (barrel).
ca_{ex}	Maximum capacity of export terminal ex (barrel)
ca_{dc}	Maximum capacity of distribution center dc (barrel).
ca_{h}	Maximum capacity of harvesting site h (ton).
ca_{c}	Maximum capacity of jatropha collection center c (ton).
ca_{p}	Maximum jatropha input capacity to pre-processing unit p (ton).
ca_{u}	Maximum capacity of upgrading unit u in biodisel supply chain (barrel).
ca_{br}	Maximum capacity of bio-refinery br (barrel).
oex_t	Selling price of crude oil to export terminals in the period t ($).
$prcu_t$	Selling price of fuel to customers in the period t ($).
$prin_t$	Selling price of fuel to industries in the period t ($).
$prex_t$	Selling price of fuel to export terminals in the period t ($).

dr	Interest rate
$d_{of,so}$	Distance between the oil field of and the crude oil storage so (km).
$d_{so,ex}$	Distance between the crude oil storage so and the export terminal ex (km).
$d_{so,du}$	Distance between the crude oil storage so and the distillation unit du (km).
$d_{du,pu}$	Distance between the distillation unit du and the refinery production unit pu (km).
$d_{pu,s}$	Distance between the refinery production unit pu and the fuel storage center s (km).
$d_{uu,s}$	Distance between the upgrading units in the gas oil supply chain uu and the fuel storage center s (km).
$d_{dc,ex}$	Distance between the distribution center dc and the export terminal ex (km).
$d_{dc,in}$	Distance between the distribution center dc and the industry in (km).
$d_{dc,cu}$	Distance between the distribution center dc and the customer cu (km).
$d_{h,c}$	Distance between the harvesting center h and the collection center c (km).
$d_{c,p}$	Distance between the collection center c and the pre-processing unit p (km).
$d_{c,br}$	Distance between the collection center c and the bio-refinery br (km).
$d_{p,so}$	Distance between the pre-processing unit p and the crude oil storage so (km).
$d_{p,u}$	Distance between the pre-processing unit p and the upgrading unit u in the biodiesel supply chain (km).
$d_{p,uu}$	Distance between the pre-processing unit p and the upgrading unit uu in the gas oil supply chain (km).
$d_{s,dc}$	Distance between the fuel storage center s and the distribution center dc (km).
$d_{u,s}$	Distance between the upgrading unit u in the biodiesel supply chain and the fuel storage center s (km).
$d_{u,dc}$	Distance between the upgrading unit u in the biodiesel supply chain and the distribution center dc (km).
$d_{br,s}$	Distance between the bio-refinery br and the fuel storage center s (km).
$d_{br,dc}$	Distance between the bio-refinery br and the distribution center dc (km).
$cprpu_t$	Processing cost of refinery production units for a barrel of intermediate product in period t ($/barrel
$cprdu_t$	Processing cost of distillation units in period t for a barrel of crude oil in period t ($/barrel)
$cpruu_t$	Processing cost of upgrading units in the gas oil supply chain for a barrel of intermediate product in period t ($/barrel)
$cpru_t$	Processing cost of upgrading units in the biodisel supply chain for a barrel of intermediate product in period t ($/barrel)
$cprbr_t$	Processing cost of bio-refineries for a ton of jatropha in period t ($/barrel)
$cprp_t$	Processing cost of pre-processing units for a ton of jatropha in period t ($/barrel)
ho_t^{so}	Cost of holding an inventory unit at the crude oil storage so in period t ($/barrel)
ho_t^{s}	Cost of holding an inventory unit at the fuel storage center s in period t ($/barrel)
ho_t^{c}	Cost of holding an inventory unit at the collection center c in period t ($/ton)
$ctr_{of,so}^t$	Cost of transporting a barrel of crude oil between the oil field of and the crude oil storage so in period t ($/barrel)
$ctr_{so,ex}^t$	Cost of transporting a barrel of crude oil between the crude oil storage so and the export terminal ex in period t ($/barrel)
$ctr_{so,du}^t$	Cost of transporting a barrel of crude oil between the crude oil storage so and the distillation unit du in period t ($/barrel)
$ctr_{du,pu}^t$	Cost of transporting a barrel of intermediate product between the distillation unit du and the refinery production unit pu in period t ($/barrel)
$ctr_{pu,s}^t$	Cost of transporting a barrel of gas oil between the refinery production unit pu and the fuel storage center s in period t ($/barrel)
$ctr_{uu,s}^t$	Cost of transporting a barrel of biodisel between the upgrading unit uu in the gas oil supply chain and the fuel storage center s in period t ($/barrel)
$ctr_{dc,ex}^t$	Cost of transporting a barrel of fuel between the distribution center dc and the export terminal ex in period t ($/barrel)
$ctr_{dc,cu}^t$	Cost of transporting a barrel of fuel between the distribution center dc and the customer cu in period t ($/barrel)
$ctr_{dc,in}^t$	Cost of transporting a barrel of fuel between the distribution center dc and the industry in in period t ($/barrel)
$ctr_{h,c}^t$	Cost of transporting a ton of jatropha between the harvesting center h and the collection center c in period t ($/barrel)
$ctr_{c,p}^t$	Cost of transporting a ton of jatropha between the collection center c and the pre-processing unit p in period t ($/barrel)

$ctr_{c,br}^{t}$	Cost of transporting a ton of jatropha between the collection center c and the bio-refinery br in period t ($/barrel)
$ctr_{p,u}^{t}$	Cost of transporting a barrel of intermediate product between the pre-processing unit p and the upgrading unit u in the biodiesel supply chain in period t ($/barrel)
$ctr_{p,uu}^{t}$	Cost of transporting a barrel of bio_oil between the pre-processing unit p and the upgrading unit uu in the gas oil supply chain in period t ($/barrel)
$ctr_{p,so}^{t}$	Cost of transporting a barrel of bio_slurry between the pre-processing unit p and the crude oil storage so in period t ($/barrel)
$ctr_{br,s}^{t}$	Cost of transporting a barrel of biodisel between the bio-refinery br and the fuel storage center s in period t ($/barrel)
$ctr_{br,dc}^{t}$	Cost of transporting a barrel of biodisel between the bio-refinery br and the distribution center dc in period t ($/barrel)
$ctr_{s,dc}^{t}$	Cost of transporting a barrel of fuel between the fuel storage center s and the distribution center dc in period t ($/barrel)
$ctr_{u,s}^{t}$	Cost of transporting a barrel of biodisel between the upgrading unit u in the biodiesel supply chain and the fuel storage center s in period t ($/barrel)
$ctr_{u,dc}^{t}$	Cost of transporting a barrel of biodisel between the upgrading unit u in the biodiesel supply chain and the distribution center dc in period t ($/barrel)
$chan$	Conversion factor of millions of barrels to the number of fuel tankers
$entr$	Amount of carbon dioxide emissions per a barrel and per unit distance due to transportation in the supply chain (ton/km.barrel)
$echan$	Reduction coefficient of carbon dioxide emissions due to biodiesel consumption instead of gas oil
$enchan$	Conversion factor number of barrels to the number of tankers carrying fuel
$alpha1$	Percentage of waste in upgrading units in the gas oil supply chain
$alpha2$	Percentage of waste in refinery production units
$alpha3$	Percentage of waste in pre-processing units
$alpha4$	Percentage of waste in bio-refineries
$alpha5$	Percentage of waste in upgrading units in the biodiesel supply chain
$\max ca$	Maximum allowable increase in refinery capacity (barrel)
$empu$	The number of jobs created by increasing the capacity of the refinery's production units
emh	The number of jobs created per hectare of Jatropha cultivation.
emc	The number of jobs created per ton capacity of the Jatropha collection center.
emp	The number of jobs created per ton of capacity of the pre-processing center.
emu	The number of jobs created per million barrels of capacity of the upgrading unit in the biodiesel supply chain
$embr$	The number of jobs created per million barrels of bio-refinery capacity.
$emuu$	The number of jobs created per million barrels of capacity of the upgrading unit in the gas oil supply chain
$emdc$	The number of jobs created per million barrels of distribution center capacity.
λ_{pu}	Significance factor of increasing / decreasing migration to the city near the pu refinery production unit
λ_{h}	Significance factor of increasing / decreasing migration to the city near the h harvesting center
λ_{c}	Significance factor of increasing / decreasing migration to the city near the c jatropha collection center
λ_{p}	Significance factor of increasing / decreasing migration to the city near the p pre-processing unit
λ_{u}	Significance factor of increasing / decreasing migration to the city near the u upgrading unit in the biodiesel supply chain
λ_{br}	Significance factor of increasing / decreasing migration to the city near the br bio-refinery
λ_{uu}	Significance factor of increasing / decreasing migration to the city near the uu upgrading unit in the gas oil supply chain
λ_{dc}	Significance factor of increasing / decreasing migration to the city near the dc distribution center
β_{pu}	Unemployment rate in the city near the pu refinery production unit
β_{h}	Unemployment rate in the city near the h harvesting center
β_{c}	Unemployment rate in the city near the c jatropha collection center
β_{p}	Unemployment rate in the city near the p pre-processing unit
β_{u}	Unemployment rate in the city near the u upgrading unit in the biodiesel supply chain
β_{uu}	Unemployment rate in the city near the uu upgrading unit in the gas oil supply chain
β_{br}	Unemployment rate in the city near the br bio-refinery
β_{dc}	Unemployment rate in the city near the dc distribution center
$prob_{se}$	Probability of occurrence of the se scenario

Binary variables	
x_t^{uu}	1 if location uu in period t is selected for constructing an upgrading unit in the gas oil supply chain ; 0 otherwise.
x_t^{h}	1 if location h in period t is selected for harvesting jatropha ; 0 otherwise.
x_t^{c}	1 if location c in period t is selected for constructing a collection center jatropha ; 0 otherwise.
x_t^{p}	1 if location p in period t is selected for constructing a pre-processing unit ; 0 otherwise.
x_t^{u}	1 if location uu in period t is selected for constructing an upgrading unit in the biodiesel supply chain ; 0 otherwise.
x_t^{dc}	1 if location dc in period t is selected for constructing a distribution center ; 0 otherwise.
x_t^{br}	1 if location br in period t is selected for constructing a bio-refinery ; 0 otherwise.
y_t^{uu}	1 if location uu is active as the upgrading unit in the gas oil supply chain in period t ; 0 otherwise.
y_t^{h}	1 if location h is active as the harvesting center in period t ; 0 otherwise.
y_t^{c}	1 if location h is active as the collection center in period t ; 0 otherwise.
y_t^{p}	1 if location p is active as the pre-processing unit in period t ; 0 otherwise.
y_t^{u}	1 if location uu is active as the upgrading unit in the biodisel supply chain in period t ; 0 otherwise.
y_t^{dc}	1 if location dc is active as the distribution center in period t ; 0 otherwise.
y_t^{br}	1 if location br is active as the bio-refinery in period t ; 0 otherwise.

Continuous variables	
$q_{se,t}^{of,so}$	Quantity of crude oil transferred from the oil field of to the crude oil storage so in period t under scenario se (barrel)
$q_{se,t}^{so,ex}$	Quantity of crude oil transferred from the crude oil storage so to the export terminal ex in period t under scenario se (barrel)
$q_{se,t}^{so,du}$	Quantity of crude oil transferred from the crude oil storage so to the distillation unit du in period t under scenario se (barrel)
$q_{se,t}^{du,pu}$	Quantity of intermediate product transferred from the distillation unit du to the refinery production unit pu in period t under scenario se (barrel)
$q_{se,t}^{du,uu}$	Quantity of intermediate product transferred from the distillation unit du to the upgrading unit uu in the gas oil supply chain in period t under scenario se (barrel)
$q_{se,t}^{pu,s}$	Quantity of gas oil transferred from the production unit pu to the fuel storage center s in period t under scenario se (barrel)
$q_{se,t}^{uu,s}$	Quantity of biodisel transferred from the upgrading unit uu in the gas oil supply chain to the fuel storage center s in period t under scenario se (barrel)
$q_{se,t}^{s,dc}$	Quantity of fuel transferred from the fuel storage center s to the distribution center dc in period t under scenario se (barrel)
$q_{se,t}^{dc,ex}$	Quantity of fuel transferred from the distribution center dc to the export terminal ex in period t under scenario se (barrel)
$q_{se,t}^{dc,cu}$	Quantity of fuel transferred from the distribution center dc to the customer cu in period t under scenario se (barrel)
$q_{se,t}^{dc,in}$	Quantity of fuel transferred from the distribution center dc to the industry in in period t under scenario se (barrel)
$q_{se,t}^{h,c}$	Quantity of jatropha transferred from the harvesting center h to the collection center c in period t under scenario se (ton)
$q_{se,t}^{c,p}$	Quantity of jatropha transferred from the collection center c to the pre-processing unit p in period t under scenario se (ton)
$q_{se,t}^{c,br}$	Quantity of jatropha transferred from the collection center c to the bio-refinery br in period t under scenario se (ton)
$q_{se,t}^{p,u}$	Quantity of intermediate product transferred from the pre-processing unit p to the upgrading unit u in the biodisel supply chain in period t under scenario se (barrel)
$q_{se,t}^{p,uu}$	Quantity of bio_oil transferred from the pre-processing unit p to the upgrading unit uu in the gas oil supply chain in period t under scenario se (barrel)
$q_{se,t}^{p,so}$	Quantity of bio_slurry transferred from the pre-processing unit p to the crude oil storage so in period t under scenario se (barrel)
$q_{se,t}^{br,dc}$	Quantity of biodisel transferred from the bio-refinery br to the distribution center dc in period t under scenario se (barrel)
$q_{se,t}^{u,dc}$	Quantity of biodisel transferred from the upgrading unit u in the biodisel supply chain to the distribution center dc in period t under scenario se (barrel)
$q_{se,t}^{br,s}$	Quantity of biodisel transferred from the bio-refinery br to the fuel storage s in period t under scenario se (barrel)
$q_{se,t}^{u,s}$	Quantity of biodisel transferred from the upgrading unit u in the biodisel supply chain to the fuel storage s in period t under scenario se (barrel)

$l_{se,t}^{pu}$	Amount of increase in the capacity of the refinery production unit pu in period t under scenario se (barrel)
$ca_{se,t}^{pu}$	Capacity of refinery production unit pu in period t under scenario se (barrel)
$inv_{se,t}^{so}$	Inventory of crude oil storage so in period t under scenario se (barrel)
$inv_{se,t}^{s}$	Inventory of fuel storage s in period t under scenario se (barrel)
$inv_{se,t}^{c}$	Inventory of collection center c in period t under scenario se (ton)
$plus_{se,t}^{so}$	The difference between inputs and outputs to the crude oil storage so in period t under scenario se (barrel)
$plus_{se,t}^{s}$	The difference between inputs and outputs to the fuel storage s in period t under scenario se (barrel)
$plus_{se,t}^{c}$	The difference between inputs and outputs to the collection center c in period t under scenario se (ton)
$ctr_{se,t}$	Transportation costs in the period t under scenario se ($)
$cop_{se,t}$	Operational costs in the period t under scenario se ($)
$cinv_{se,t}$	Investment costs in the period t under scenario se ($)
$ch_{se,t}$	Holding costs in the period t under scenario se ($)
$inc_{se,t}$	Income in the period t under scenario se ($)
$\cos t$	The present value of supply chain costs on the planning horizon ($)
$income$	The present value of supply chain revenue on the planning horizon ($)
$profit$	Amount of economic objective function_The present value of the supply chain profit on the planning horizon_($)
$envi_{se,t}$	Amount of reduction due to the emission of carbon dioxide due to the consumption of biodiesel (instead of fossil fuels) in the period t under scenario se (ton)
$envt_{se,t}$	Amount of carbon dioxide emissions due to total supply chain transportation in the period t under scenario se (ton)
$enviro$	Amount of environmental objective function (ton)
$soc_{se,t}$	Amount of social objective function in the period t under scenario se ($ / period)
$social$	Amount of social objective function

3-2- Problem modeling

Considering the above notations, the mathematical modeling of the problem is given in equations (1) to (65) as follows**:**

- Economic objective function

The net present value of profit is equal to the net present value of incomes minus the net present value of costs.

$$\max profit = income - \cos t \qquad (1)$$

The net present value of income is obtained by converting the income of each period to the present value and summing them for all scenarios and periods according to equation2.

$$income = \sum_{se} \sum_{t=1}^{T} (1+dr)^{-(t-1)} \,.\, inc_{se,t} \,.\, prob_{se} \qquad (2)$$

The income of each period for each scenario according to equation 3 is obtained from the total income of product sales (gas oil/biodiesel) to local customers, industries, and export centers, as well as the sale of crude oil to export centers. The income of each is multiplied by the amount of sales in the scenario in the respective sales price. These four revenue elements are shown in equation 3.

$$inc_{se,t} = \sum_{ex} \sum_{so} q_{se,t}^{so,ex} \,.oex_t + \sum_{ex} \sum_{dc} q_{se,t}^{dc,ex} \,.\, prex_t + \sum_{in} \sum_{dc} q_{se,t}^{dc,in} \,.\, prin_t + \sum_{cu} \sum_{dc} q_{se,t}^{dc,cu} \,.\, prcu_t \qquad \forall t, se \qquad (3)$$

Similar to the present value of total income, to obtain the present value of total cost, we convert the types of costs of each period into present value and obtain the sum of them for all periods and scenarios. This is shown in equation 4.

$$\cos t = \sum_{se} \sum_{t=1}^{T} (1+dr)^{-(t-1)} .(cinv_{se,t} + cop_{se,t} + ctr_{se,t} + ch_{se,t}).prob_{se} \qquad (4)$$

According to equation 4, costs consist of several elements: investment costs, operating costs, transportation costs and inventory holding costs. Investment costs according to equation 5 are obtained from the sum of the costs of constructing potential centers and the costs of expanding the capacity of refinery production units. For each of the elements, if the binary variable is related to the construction of the value of 1, the construction cost is taken into account according to the capacity intended for it. To increase the capacity of the refinery production units, the amount of capacity increase, and the cost of increasing the capacity of a refinery production unit are included in the investment costs.

$$cinv_{se,t} = \sum_{uu} cc_t^{uu}.x_{uu,t} + \sum_{h} cc_t^{h}.x_{h,t}.ca_h + \sum_{c} cc_t^{c}.x_{c,t} + \sum_{p} cc_t^{p}.x_{p,t} + \sum_{u} cc_t^{u}.x_{u,t} + \sum_{dc} cc_t^{dc}.x_{dc,t}$$

$$+ \sum_{br} cc_t^{br}.x_{br,t} + \sum_{pu} cc_t^{pu}.l_{se,t}^{pu} \qquad \forall t, se \qquad (5)$$

The second element in costs is the operating costs that are obtained according to equation 6. Operating costs are taken into account in the processing units. These units are distillation towers, gas oil supply chain upgrading units, biodiesel supply chain upgrading units, pre-processing centers, refinery production units and bio-refineries. Operating costs depend on the amount of production in the unit.

$$cop_{se,t} = \sum_{du} \sum_{so} cprdu_t .q_{se,t}^{so,du} + \sum_{uu} \sum_{du} cpruu_t .q_{se,t}^{du,uu} + \sum_{pu} \sum_{du} cprpu_t .q_{se,t}^{pu,du} + \sum_{p} \sum_{c} cprp_t .q_{se,t}^{c,p}$$

$$+ \sum_{u} \sum_{p} cpru_t .q_{se,t}^{p,u} + \sum_{br} \sum_{c} cprbr_t .q_{se,t}^{c,br} \qquad \forall t, se \qquad (6)$$

The third cost element is transportation costs, which are obtained according to equation 7. Transportation costs between all network units are considered for the transporting of feedstock, intermediate products and, final product transportation costs also depend on the amount of transportation. Fixed transportation cost is not considered.

$$ctr_{se,t} = chan.(\sum_{so} \sum_{of} ctr_{of,so}^{t} .q_{se,t}^{of,so} + \sum_{ex} \sum_{so} ctr_{so,ex}^{t} .q_{se,t}^{so,ex} + \sum_{du} \sum_{so} ctr_{so,du}^{t} .q_{se,t}^{so,du} + \sum_{pu} \sum_{du} ctr_{du,pu}^{t} .q_{se,t}^{du,pu}$$

$$+ \sum_{uu} \sum_{du} ctr_{du,uu}^{t} .q_{se,t}^{du,uu} + \sum_{s} \sum_{pu} ctr_{pu,s}^{t} .q_{se,t}^{pu,s} + \sum_{s} \sum_{uu} ctr_{uu,s}^{t} .q_{se,t}^{uu,s} + \sum_{dc} \sum_{s} ctr_{s,dc}^{t} .q_{se,t}^{s,dc}$$

$$+ \sum_{ex} \sum_{dc} ctr_{dc,ex}^{t} .q_{se,t}^{dc,ex} + \sum_{cu} \sum_{dc} ctr_{dc,cu}^{t} .q_{se,t}^{dc,cu} + \sum_{in} \sum_{dc} ctr_{dc,in}^{t} .q_{se,t}^{dc,in} + \sum_{c} \sum_{h} ctr_{h,c}^{t} .q_{se,t}^{h,c}$$

$$+ \sum_{p} \sum_{c} ctr_{c,p}^{t} .q_{se,t}^{c,p} + \sum_{br} \sum_{c} ctr_{c,br}^{t} .q_{se,t}^{c,br} + \sum_{u} \sum_{p} ctr_{p,u}^{t} .q_{se,t}^{p,u} + \sum_{uu} \sum_{p} ctr_{p,uu}^{t} .q_{se,t}^{p,uu} + \sum_{so} \sum_{p} ctr_{p,so}^{t} .q_{se,t}^{p,so}$$

$$+ \sum_{s} \sum_{br} ctr_{br,s}^{t} .q_{se,t}^{br,s} + \sum_{dc} \sum_{br} ctr_{br,dc}^{t} .q_{se,t}^{br,dc} + \sum_{s} \sum_{u} ctr_{u,s}^{t} .q_{se,t}^{u,s} + \sum_{dc} \sum_{u} ctr_{u,dc}^{t} .q_{se,t}^{u,dc}) \qquad \forall t, se \qquad (7)$$

The fourth cost element is inventory holding costs, which are obtained according to equation 8. This cost is calculated for Jatropha collection centers, crude oil storage centers and, final product storage centers.

$$ch_{se,t} = \sum_{so} inv^{so}_{se,t}.ho^{so}_{t} + \sum_{s} inv^{s}_{se,t}.ho^{s}_{t} + \sum_{c} inv^{c}_{se,t}.ho^{c}_{t} \qquad \forall t,se \qquad (8)$$

- Environmental objective function

In this study, the environmental objective function is obtained from the difference between the two equations. In the first equation, the goal is to reduce the amount of carbon dioxide emissions created by intra-chain shipments. In the second equation, the goal is to increase the savings in carbon dioxide emissions by replacing biodiesel with gas oil. This is shown in equation 9.

$$enviro = \sum_{se}\sum_{t=1}^{T}(envt_{se,t} - envi_{se,t}) * prob_{se} \qquad (9)$$

In equation 10, according to the amount of carbon dioxide emissions per unit distance traveled within the network, the amount of transmissions within the network, and the distance between different facilities, the amount of carbon dioxide emissions is obtained through intranet transport.

$$\begin{aligned}envt_{se,t} = enchan.(&\sum_{of}\sum_{so} entr.q^{of,so}_{se,t}.d^{of,so} + \sum_{so}\sum_{ex} entr.q^{so,ex}_{se,t}.d^{so,ex} + \sum_{so}\sum_{du} entr.q^{so,du}_{se,t}.d^{so,du} \\ &+ \sum_{du}\sum_{pu} entr.q^{du,pu}_{se,t}.d^{du,pu} + \sum_{pu}\sum_{s} entr.q^{pu,s}_{se,t}.d^{pu,s} + \sum_{uu}\sum_{s} entr.q^{uu,s}_{se,t}.d^{uu,s} + \sum_{s}\sum_{dc} entr.q^{s,dc}_{se,t}.d^{s,dc} \\ &+ \sum_{dc}\sum_{ex} entr.q^{dc,ex}_{se,t}.d^{dc,ex} + \sum_{dc}\sum_{cu} entr.q^{dc,cu}_{se,t}.d^{dc,cu} + \sum_{dc}\sum_{in} entr.q^{dc,in}_{se,t}.d^{dc,in} + \sum_{h}\sum_{c} entr.q^{h,c}_{se,t}.d^{h,c} \\ &+ \sum_{c}\sum_{p} entr.q^{c,p}_{se,t}.d^{c,p} + \sum_{c}\sum_{br} entr.q^{c,br}_{se,t}.d^{c,br} + \sum_{p}\sum_{u} entr.q^{p,u}_{se,t}.d^{p,u} + \sum_{p}\sum_{uu} entr.q^{p,uu}_{se,t}.d^{p,uu} \\ &+ \sum_{p}\sum_{so} entr.q^{p,so}_{se,t}.d^{p,so} + \sum_{br}\sum_{s} entr.q^{br,s}_{se,t}.d^{br,s} + \sum_{br}\sum_{dc} entr.q^{br,dc}_{se,t}.d^{br,dc} + \sum_{u}\sum_{s} entr.q^{u,s}_{se,t}.d^{u,s} \\ &+ \sum_{u}\sum_{dc} entr.q^{u,dc}_{se,t}.d^{u,dc}) \qquad \forall t,se \qquad (10)\end{aligned}$$

In equation 11, according to the amount of biodiesel produced from different units of the supply chain and also the coefficient of showing the reduction in carbon dioxide emissions due to the use of biodiesel instead of gas oil, the amount of carbon dioxide emission reduction is obtained.

$$envi_{se,t} = echan*(\sum_{uu}\sum_{s} q^{uu,s}_{se,t} + \sum_{br}\sum_{s} q^{br,s}_{se,t} + \sum_{br}\sum_{dc} q^{br,dc}_{se,t} + \sum_{u}\sum_{s} q^{u,s}_{se,t} + \sum_{u}\sum_{dc} q^{u,dc}_{se,t}) \qquad \forall t,se \qquad (11)$$

- Social objective function

Several factors have been considered in modeling the social objective function; The first is how the unemployment rate in the neighboring city facilitates construction. Because the unemployment rate is a social factor influencing the construction of a production unit. Secondly, what is the importance of migrating to a nearby city. The importance of immigration is considered in several ways. The first is that migration to the country's metropolises is not desirable, and this has been shown by considering a coefficient of less than one for metropolises. Secondly, one of the important dangers for countries is the decrease in the population of border cities and the emptying of borders and migration from these cities.

Therefore, migration to border cities is desirable and this importance with a coefficient greater than 1, is shown. In addition to the unemployment rate and the importance of migrating to each city, the number of jobs created per facility is also taken into account. This number depends on its capacity to facilitate. Therefore, the multiply of the five elements determines the amount of employment created by construction, the unemployment rate, the importance of migration, the capacity of facilitating, and the binary variables determine the desired value of the social objective function for each facilitation. Equations 12 and 13 deal with the modeling of the social objective function.

$$social = \sum_{se} \sum_{t=1}^{T} soc_{se,t} \; * prob_{se,t} \tag{12}$$

$$\begin{aligned} soc_{se,t} = {} & (\sum_{pu} l^{pu}_{se,t} * empu * \lambda pu^{pu} * \beta pu^{pu}) + (\sum_{h} cah_{h} * xh_{h,t} * emh * \lambda h^{h} * \beta h^{h}) \\ & + (\sum_{c} cac_{c} * xc_{c,t} * emc * \lambda c^{c} * \beta c^{c}) + (\sum_{p} cap_{p} * xp_{p,t} * emp * \lambda p^{p} * \beta p^{p}) \\ & + (\sum_{u} cau_{u} * xu_{u,t} * emu * \lambda u^{u} * \beta u^{u}) + (\sum_{br} cabr_{br} * xbr_{br,t} * embr * \lambda br^{br} * \beta br^{br}) \\ & + (\sum_{uu} cauu_{uu} * xuu_{uu,t} * emuu * \lambda uu^{uu} * \beta uu^{uu}) + (\sum_{dc} cadc_{dc} * xdc_{dc,t} * emdc * \lambda dc^{dc} * \beta dc^{dc}) \\ & \forall t, se \end{aligned} \tag{13}$$

- Constraints

Material balance constraints: Equations 14 to 22 show the equilibrium between the inputs and outputs of network elements. In some of them, due to waste and loss of inputs in that element, the output value is less than the input value, which is formulated by considering the effective coefficient for that element. Gas oil supply chain upgrading units, refinery production units, pre-processing units, bio-refineries, and biodiesel supply chain upgrading units are not fully efficient and need an effective coefficient.

$$\sum_{of} q^{of,so}_{se,t} + \sum_{p} q^{p,so}_{se,t} = \sum_{du} q^{so,du}_{se,t} + \sum_{ex} q^{so,ex}_{se,t} + plus^{so}_{se,t} \qquad \forall so, se, t \tag{14}$$

$$\sum_{so} q^{so,du}_{se,t} = \sum_{pu} q^{du,pu}_{se,t} \qquad \forall du, se, t \tag{15}$$

$$(1 - alpha1).\sum_{p} q^{p,uu}_{se,t} = \sum_{s} q^{uu,s}_{se,t} \qquad \forall uu, se, t \tag{16}$$

$$(1 - alpha2).\sum_{du} q^{du,pu}_{se,t} = \sum_{s} q^{pu,s}_{se,t} \qquad \forall pu, se, t \tag{17}$$

$$\sum_{uu} q^{uu,s}_{se,t} + \sum_{br} q^{br,s}_{se,t} + \sum_{u} q^{u,s}_{se,t} + \sum_{pu} q^{pu,s}_{se,t} = \sum_{dc} q^{s,dc}_{se,t} + plus^{s}_{se,t} \qquad \forall s, se, t \tag{18}$$

$$\sum_{h} q^{h,c}_{se,t} = \sum_{p} q^{c,p}_{se,t} + \sum_{br} q^{c,br}_{se,t} + plus^{c}_{se,t} \qquad \forall c, se, t \tag{19}$$

$$(1 - alpha3).\sum_{c} q^{c,p}_{se,t} = \sum_{so} q^{p,so}_{se,t} + \sum_{u} q^{p,u}_{se,t} + \sum_{uu} q^{p,uu}_{se,t} \qquad \forall p, se, t \tag{20}$$

$$(1 - alpha4).\sum_{c} q^{c,br}_{se,t} = \sum_{s} q^{br,s}_{se,t} + \sum_{dc} q^{br,dc}_{se,t} \qquad \forall br, se, t \tag{21}$$

$$(1 - alpha5).\sum_{p} q^{p,u}_{se,t} = \sum_{s} q^{u,s}_{se,t} + \sum_{dc} q^{u,dc}_{se,t} \qquad \forall u, se, t \tag{22}$$

$$\sum_{u} q^{u,dc}_{se,t} + \sum_{br} q^{br,dc}_{se,t} + \sum_{s} q^{s,dc}_{se,t} = \sum_{ex} q^{dc,ex}_{se,t} + \sum_{in} q^{dc,in}_{se,t} + \sum_{cu} q^{dc,cu}_{se,t} \qquad \forall dc, se, t \tag{23}$$

Demand constraint: Equations 24 to 27 show demand satisfaction. Equation 24 shows the satisfaction of crude oil demand for export terminals. Equation 25 shows the satisfaction of product demand for export terminals. Equation 26 shows the satisfaction of product demand for local customers and equation 27 shows the satisfaction of product demand for industries.

$$\sum_{so} q_{se,t}^{so,ex} \geq dex_{se,t}^{ex} \qquad \forall ex,se,t \qquad (24)$$

$$\sum_{dc} q_{se,t}^{dc,ex} \geq dpr_{se,t}^{ex} \qquad \forall ex,se,t \qquad (25)$$

$$\sum_{dc} q_{se,t}^{dc,cu} \geq dpr_{t}^{cu} \qquad \forall cu,se,t \qquad (26)$$

$$\sum_{dc} q_{se,t}^{dc,in} \geq dpr_{t}^{in} \qquad \forall in,se,t \qquad (27)$$

Capacity constraint: Equations 28 to 41 are related to the capacity of network elements to inputs and outputs. For potential points, it first checks the availability of that location, if available it considers the capacity of that location to enter and exit the stream. In the case of refinery production units, their capacity changes due to the possibility of increasing production capacity, which is shown in equations 32 and 33.

$$\sum_{so} q_{se,t}^{of,so} \leq ca_{of} \qquad \forall of,se,t \qquad (28)$$

$$\sum_{of} q_{se,t}^{of,so} + \sum_{p} q_{se,t}^{p,so} \leq ca_{so} \qquad \forall so,se,t \qquad (29)$$

$$\sum_{so} q_{se,t}^{so,du} \leq ca_{du} \qquad \forall du,se,t \qquad (30)$$

$$\sum_{p} q_{se,t}^{p,uu} \leq ca_{uu} \, . y_{uu,t} \qquad \forall uu,se,t \qquad (31)$$

$$\sum_{du} q_{se,t}^{du,pu} \leq ca_{se,t}^{pu} \qquad \forall pu,se,t \qquad (32)$$

$$ca_{s,t+1}^{pu} \leq ca_{s,t}^{pu} + l_{s,t+1}^{pu} \qquad \forall pu,se,t \qquad (33)$$

$$\sum_{uu} q_{se,t}^{uu,s} + \sum_{br} q_{se,t}^{br,s} + \sum_{pu} q_{se,t}^{pu,s} + \sum_{u} q_{se,t}^{u,s} \leq ca_{s} \qquad \forall s,se,t \qquad (34)$$

$$\sum_{so} q_{se,t}^{so,ex} + \sum_{dc} q_{se,t}^{dc,ex} \leq ca_{ex} \qquad \forall ex,se,t \qquad (35)$$

$$\sum_{c} q_{se,t}^{h,c} \leq ca_{h} \, . y_{h,t} \qquad \forall h,se,t \qquad (36)$$

$$\sum_{h} q_{se,t}^{h,c} \leq ca_{c} \, . y_{c,t} \qquad \forall c,se,t \qquad (37)$$

$$\sum_{c} q_{se,t}^{c,p} \leq ca_{p} \, . y_{p,t} \qquad \forall p,se,t \qquad (38)$$

$$\sum_{c} q_{se,t}^{c,br} \leq ca_{br} \, . y_{br,t} \qquad \forall br,se,t \qquad (39)$$

$$\sum_{p} q_{se,t}^{p,u} \leq ca_{u} \, . y_{u,t} \qquad \forall u,se,t \qquad (40)$$

$$\sum_{br} q_{se,t}^{br,dc} + \sum_{u} q_{se,t}^{u,dc} + \sum_{s} q_{se,t}^{s,dc} \leq ca_{dc} \, . y_{dc,t} \qquad \forall dc,se,t \qquad (41)$$

Logical constraints: The two binary variables X and Y are defined as "construct" and "availability", which are shown in equations 42 to 55 to be the relationship between the two variables. A place can only be available in one period if it is either constructed in that period or was available in the previous period as shown in equations 42 to 48. Also, a facility is available for the first period when it was built in the same period. This is shown in equations 49 to 55.

$$y_{uu,t} = y_{uu,t-1} + x_{uu,t} \qquad \forall uu, t > 1 \qquad (42)$$

$$y_{h,t} = y_{h,t-1} + x_{h,t} \qquad \forall h, t > 1 \qquad (43)$$

$$y_{c,t} = y_{c,t-1} + x_{c,t} \qquad \forall c, t > 1 \qquad (44)$$

$$y_{p,t} = y_{p,t-1} + x_{p,t} \qquad \forall p, t > 1 \qquad (45)$$

$$y_{u,t} = y_{u,t-1} + x_{u,t} \qquad \forall u, t > 1 \qquad (46)$$

$$y_{br,t} = y_{br,t-1} + x_{br,t} \qquad \forall br, t > 1 \qquad (47)$$

$$y_{dc,t} = y_{dc,t-1} + x_{dc,t} \qquad \forall dc, t > 1 \qquad (48)$$

$$y_{uu,t} = x_{uu,t} \qquad \forall uu, t = 1 \qquad (49)$$

$$y_{h,t} = x_{h,t} \qquad \forall h, t = 1 \qquad (50)$$

$$y_{c,t} = x_{c,t} \qquad \forall c, t = 1 \qquad (51)$$

$$y_{p,t} = x_{p,t} \qquad \forall p, t = 1 \qquad (52)$$

$$y_{u,t} = x_{u,t} \qquad \forall u, t = 1 \qquad (53)$$

$$y_{br,t} = x_{br,t} \qquad \forall br, t = 1 \qquad (54)$$

$$y_{dc,t} = x_{dc,t} \qquad \forall dc, t = 1 \qquad (55)$$

The increase in the capacity of refinery production units may not exceed a certain limit. It is also possible to increase capacity from the second period. These can be seen in equations 56 and 57.

$$l_{se,t}^{pu} = 0 \qquad \forall pu, se, t = 1 \qquad (56)$$

$$\sum_{t} l_{se,t}^{pu} \leq \max ca \qquad \forall pu, se \qquad (57)$$

Inventory constraint: The inventory in each period is equal to the sum of the inventory of the previous period and the difference between the inputs and outputs of the flow for each storage center in that period. This can be seen in equations 58 to 60.

$$inv_{se,t+1}^{so} = inv_{se,t}^{so} + plus_{se,t+1}^{so} \qquad \forall so, se, t \qquad (58)$$

$$inv_{se,t+1}^{s} = inv_{se,t}^{s} + plus_{se,t+1}^{s} \qquad \forall s, se, t \qquad (59)$$

$$inv_{se,t+1}^{c} = inv_{se,t}^{c} + plus_{se,t+1}^{c} \qquad \forall c, se, t \qquad (60)$$

For the first period, the inventory of each storage center is equal to the difference between the inputs and outputs of the first period flow in that storage center. This can be seen in equations 61 to 63.

$$inv_{se,t}^{so} = plus_{se,t}^{so} \qquad \forall so, se, t = 1 \qquad (61)$$

$$inv_{se,t}^{s} = plus_{se,t}^{s} \qquad \forall s, se, t = 1 \qquad (62)$$

$$inv_{se,t}^{c} = plus_{se,t}^{c} \qquad \forall c, se, t = 1 \qquad (63)$$

Definition of variables: Determination of continuous and binary variables can be seen in equations 64 and 65.

$$x_t^{uu}, x_t^{h}, x_t^{c}, x_t^{p}, x_t^{u}, x_t^{dc}, x_t^{br}, y_t^{uu}, y_t^{h}, y_t^{c}, y_t^{p}, y_t^{u}, y_t^{dc}, y_t^{br} \in \{0,1\} \tag{64}$$

$$\begin{gathered} q_{se,t}^{of,so}, q_{se,t}^{so,ex}, q_{se,t}^{so,du}, q_{se,t}^{du,pu}, q_{se,t}^{pu,s}, q_{se,t}^{uu,s}, q_{se,t}^{s,dc}, q_{se,t}^{dc,ex}, q_{se,t}^{dc,cu}, q_{se,t}^{dc,in}, q_{se,t}^{h,c}, q_{se,t}^{c,p}, q_{se,t}^{c,br}, q_{se,t}^{p,u}, q_{se,t}^{p,uu}, q_{se,t}^{p,so}, \\ q_{se,t}^{br,dc}, q_{se,t}^{u,dc}, q_{se,t}^{u,s}, q_{se,t}^{br,s}, l_{se,t}^{pu}, ca_{se,t}^{pu}, inv_{se,t}^{so}, inv_{se,t}^{s}, inv_{se,t}^{c}, plus_{se,t}^{so}, plus_{se,t}^{s}, plus_{se,t}^{c}, ctr_{se,t}, cop_{se,t}, \\ cinv_{se,t}, ch_{se,t}, inc_{se,t}, \mathrm{cos}t, income, profit, envi_{se,t}, envt_{se,t}, enviro, soc_{se,t}, social \geq 0 \end{gathered} \tag{65}$$

4- Solution approach

The augmented epsilon constraint method is one of the methods for solving multi-objective problems. In this method, first ε is related to each of the objective functions and one function is considered as the objective function and the rest as the constraint and the single-objective model is solved. This method has two main problems: 1. The optimal area of each of the objective functions is not determined in the efficient answer set. 2. Inefficient answers have emerged. To address these shortcomings, an augmented epsilon constraint method is proposed that produces only efficient solutions.

Table 1. Payoff results of the objectives for integrated supply chains

	Solve with economic objective function	Solve with environmental objective function	Solve with social objective function	Worst amount	Best amount
The value of the economic objective function (milliard dollars / 20 years)	6523.99	6467.89	6522.04	6467.89	6523.99
The value of the environmental objective function (million tons / 20 years)	1199.08	972.96	1197.61	1199.08	972.96
The value of the social objective function (divided by thousand)	726.2	1707.18	1707.18	726.2	1707.18

The augmented epsilon constraint method provides optimal Pareto, efficient solutions. In the epsilon constraint method, one of the objective functions is considered as the main objective function to be optimized, while the other objective function is considered as a constraint in the model. For this purpose, first, the model is solved separately for each of the objective functions and the values of the other objective functions are specified in each step. The minimum and maximum values for each objective function are then specified. This information is summarized in table 1.

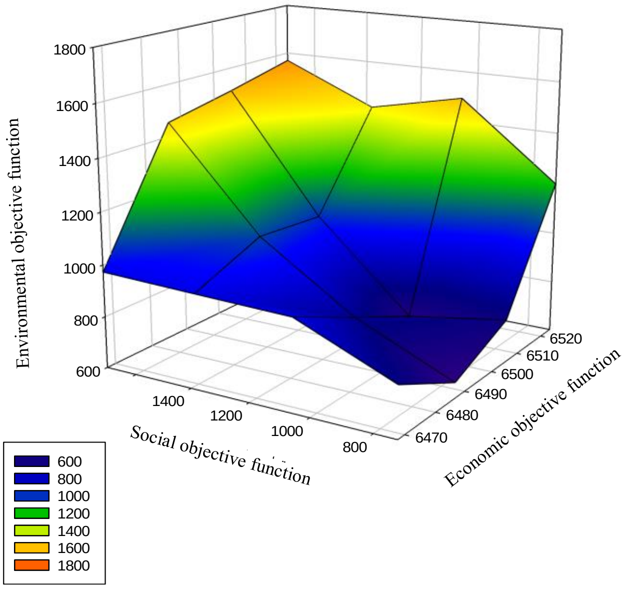

Fig. 2. Surface representation of the pareto optimal solutions

As shown in figure 2, since the function has three objectives, the Pareto boundary is defined as surface. This surface is composed according to the points obtained from different epsilons, and the points on it are the optimal points that are selected from the final point according to the decision of the decision maker. As shown in figure 2, as the economic objective function increases, so does the environmental objective function, which was predictable; Because in order to improve the economic objective function in terms of construction of various facilities, the use of biodiesel supply chain capacity and inter-chain transportation only pays attention to economic issues and increases carbon dioxide emissions. Also, as the value of the economic objective function increases, the value of the social objective function decreases. This is because in order to increase the function of the social goal, it is necessary to build more facilities that are not economically desirable.

5- Case study and analysis of results

In order to show the performance of the proposed model, the gas oil and biodiesel supply network in Iran has been studied. After the equations in the model are solved and the answers are obtained, the set of network points will be in the form of figure 3. The planned network includes forty-four oil fields, sixteen crude oil storage centers, eleven export terminals, nine distillation towers and refinery production units, nine potential locations for gas oil supply chain upgrading units, nine gas oil and, biodiesel storage centers, ten potential locations of Jatropha harvesting, ten potential Jatropha storage locations, ten potential preprocessing locations, six potential locations for biodiesel supply chain upgrading units, six potential bio-refinery locations, thirty-seven potential distribution centers, thirty-one local customer centers, and finally forty-three industrial centers. The time horizon is twenty years.

5-1- Sensitivity analysis

By considering that this model has been developed and resolved over a 20-year time horizon, it is necessary to examine the effects of changes in demand over the years. In this regard, we analyze the effect of demand changes up to ten percent more on model elements. Given that the importance of economic, environmental and social objectives varies in different years according to the policies adopted, these analyzes are performed for all three goal functions. Figure 4 shows the changes in the value of the economic objective function relative to the changes in demand values for different amounts of epsilon. This percentage change has occurred in all types of demand, including crude oil export demand, gas oil or biodiesel export demand, industrial gas oil or biodiesel demand, and gas oil or biodiesel demand from customers. As can be seen, with increasing demand, the amount of total profit first increases and then decreases. In other words, as demand increases by a certain amount, although revenue increases, the rate of increase in costs to meet that demand is greater than the increase in revenue.

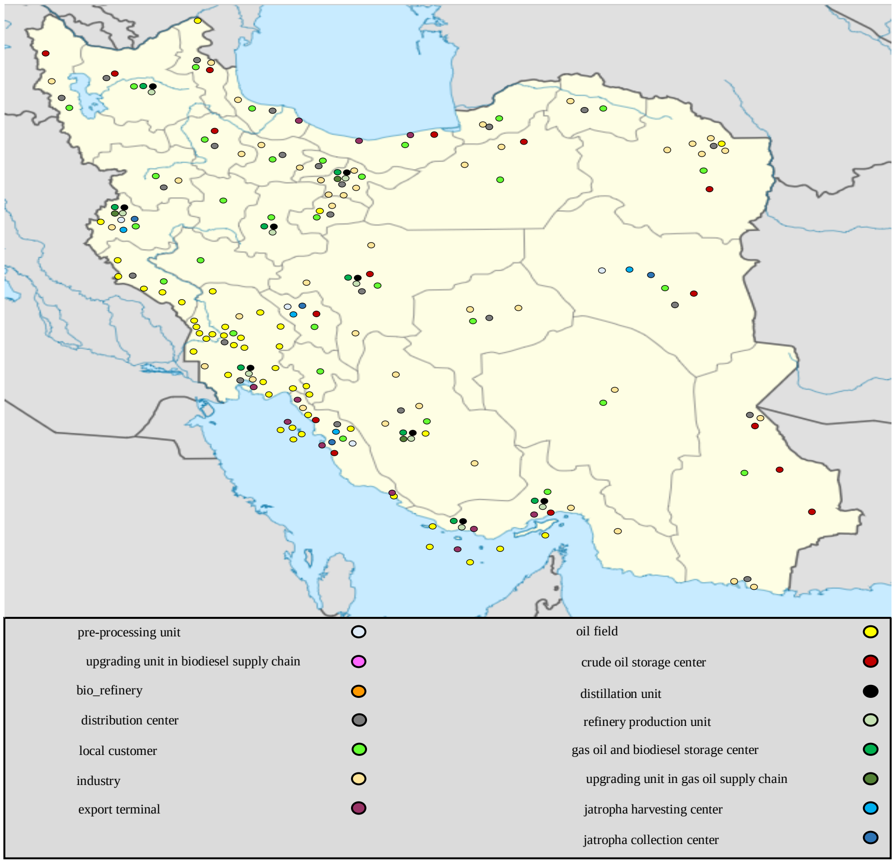

Fig. 3. Actual points in the network of case study

Figure 5 shows the changes in the value of the environmental objective function relative to the changes in the demand values. As can be seen, the value of the environmental objective function increases as demand increases as expected. Also, with increasing ε3, the amount of environmental effects decreases.

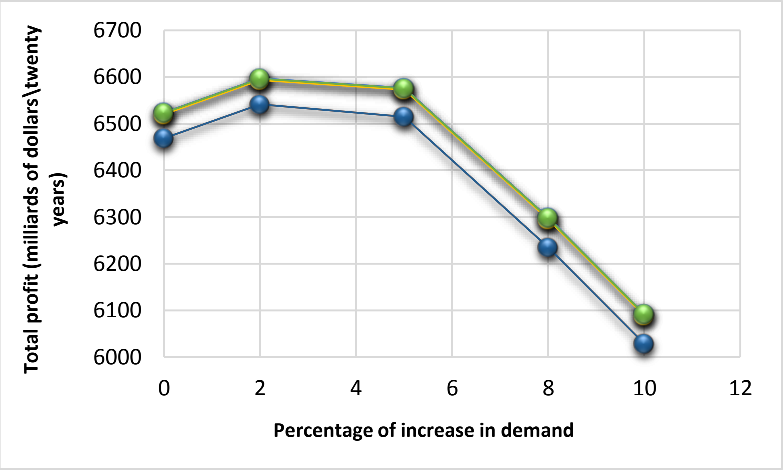

Fig. 4. Changes in total profits with increase in demand

Figure 6 shows the changes in the value of the social objective function in exchange for changes in demand for different epsilons. Changes in total profit relative to price changes can be seen in figure 7. As it is known, due to the higher price and high volume of exports, the greatest impact on total profit is related to changes in export prices. The least impact is related to changes in sales prices to industries. Because industries have less demand than other customers.

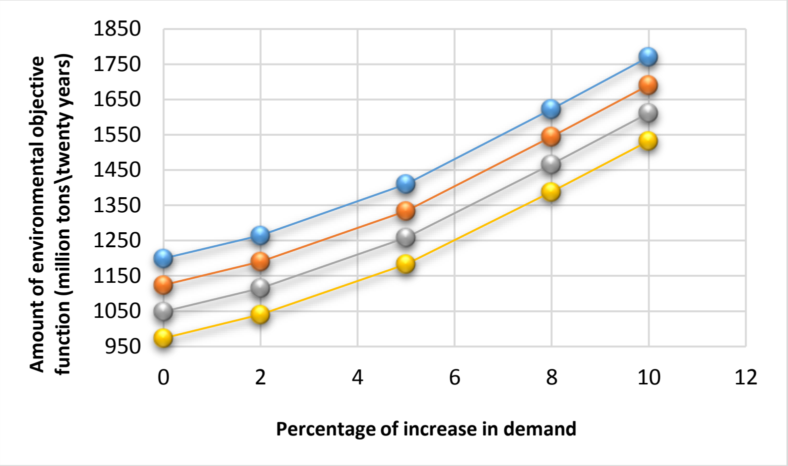

Fig. 5. Changes in environmental objective function with increase in demand

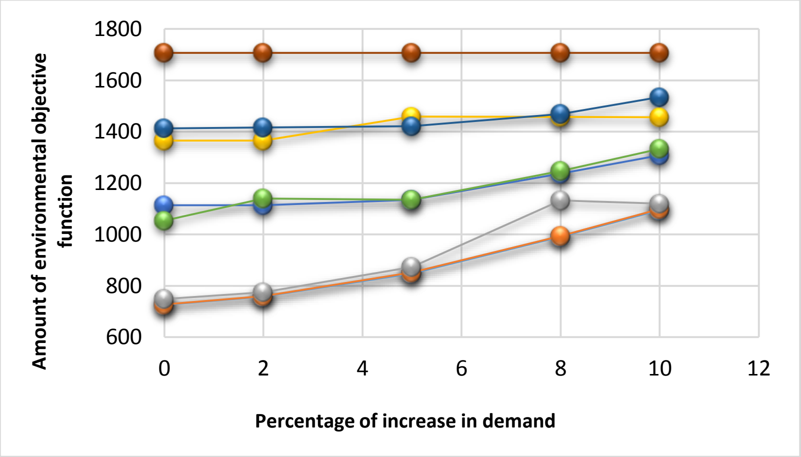

Fig. 6. Changes in social objective function with increase in demand

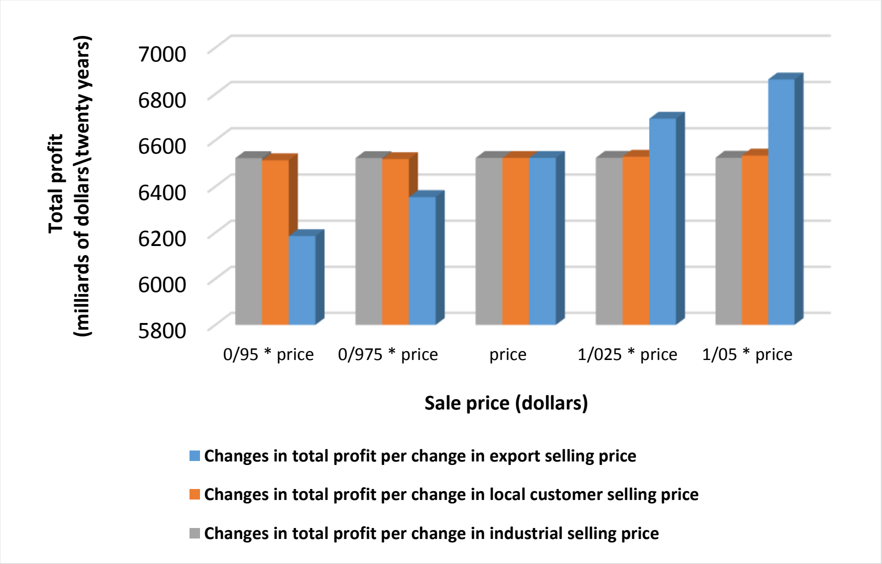

Fig. 7. Total profit changes with changes in selling prices

5-2- Validation of the model according to the case study

To investigate the effects of the integration of the two supply chains, we solve the model for the case where the two chains are separate from each other and go through each from the beginning to reach the final customers. The results of solving the model in the case of the non-integration of two supply chains are described in table 2.

As can be seen, the values of the objective function worsened for all three economic, environmental, and social objective functions. The reason for this is that due to the cost of construction of biodiesel supply chain facilities, the model is less inclined to produce biodiesel, and this increases gas oil production and consequently increases environmental pollution. On the other hand, this reduces job creation and other social effects described in the previous sections. Also, due to the fact that for cases where the biofuel supply chain is active for biodiesel production, it is necessary to build all the facilities of the chain, investment costs will increase. On the other hand, due to the separation of the two chains, transportation costs increase. Figure 8 compares the best values of each of the objective functions in the two modes of integration of the two chains with the infrastructure of the gas oil supply chain and the lack of integration and separate operation of the two supply chains. As mentioned, all objective functions in the proposed model are improved.

Table 2. Payoff results of the objectives for non-integrated supply chains

	Solve with economic objective function	Solve with environmental objective function	Solve with social objective function	Worst amount	Best amount
The value of the economic objective function (milliard dollars / 20 years)	5841.25	5518.21	5695.45	5518.21	5841.25
The value of the environmental objective function (million tons / 20 years)	1478.13	1257.95	1369.25	1478.13	1257.95
The value of the social objective function (divided by thousand)	548.39	1298.56	1310.47	548.39	1310.47

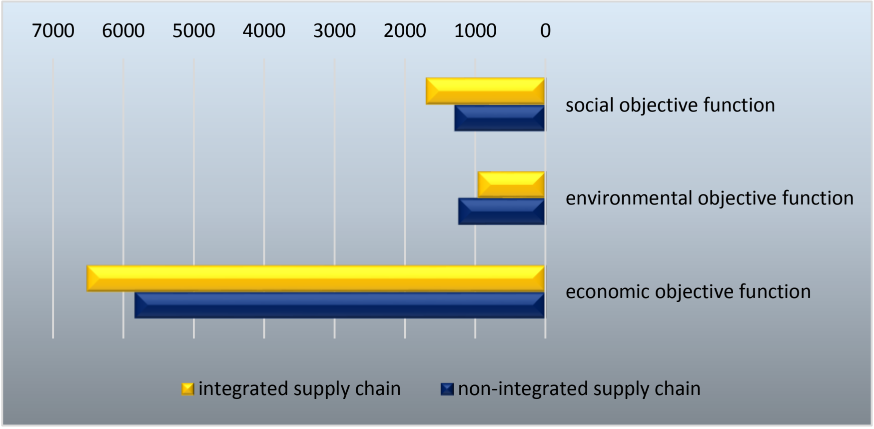

Fig. 8. Comparision of best amount of objective functions for integrated and non-integrated supply chains

6- Conclusions and future suggestions

In this research, an integrated supply chain of gas oil and biodiesel with a sustainable development approach was designed. The proposed model has three goals that constitute the three elements of sustainable development, namely economic, environmental, and social goals. The economic objective function seeks to maximize the net present value of profit that results from the difference between the amounts of incomes and costs. In terms of revenues, different types of revenues, such as export sales, are referred as local industries and customers. On the other hand, various elements such as investment costs, operating costs, inventory holding costs and, transportation costs have been considered. The environmental objective function seeks to minimize environmental pollution. This goal is achieved in two ways; The first is to reduce carbon dioxide emissions from intra-chain shipments, and the second is to increase carbon dioxide savings due to the use of biodiesel instead of gas oil by customers. The social goal function seeks to maximize social goals such as migration to the border areas of the country due to security issues and lack of migration to metropolitan areas, eliminating unemployment in cities with high unemployment rates and, creating more employment. Finally, the final model for Iran was studied as a case study and, the augmented epsilon constraint method was used to solve the model and, the results were analyzed. The results of the model showed that the integration of the two chains improves all three functions of economic, environmental and social goals. In order to develop the proposed model, it is possible to consider issues such as risk issues in the supply chain, including political and atmospheric risks, etc., to consider various government incentives in the supply chain of biofuels, to consider third-generation biomass or biomasses such as animal waste, municipal and industrial waste and effluents with high potential for fuel production were mentioned.

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