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An integrated gas-oil and bio-diesel supply network model with strategic and tactical applications considering the environmental aspects

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Abstract. In recent years, research has shown that biomass can be a source of energy to replace fossil fuels and effectively reduce current environmental crises. Researchers have studied how biofuels are supplied through the oil supply chain to achieve tangible results. This paper presents an optimization model for the gas-oil and bio-diesel supply chains suggesting the optimization of both supply chains simultaneously for the first time. The proposed model deals with the connection points of two supply chains and determines the two chains' connection points by considering two economic and environmental objective functions. The model can be used to make decisions on issues such as location, allocation, production planning, inventory management, capacity expansion, and so forth. The proposed programming model's performance has been studied through a real case study in Iran and the sensitivity analyses have been performed. The e-constraint method was used to solve the multi-objective model. The proposed model is expected to be effective in the future management of countries' fuel sources, particularly to be used as an alternative to fossil fuels. Also, this research can provide a basis for more extensive research on fuel supply chain integration.

1 Introduction

Current global energy consumption shows a significant upward trend by 2030. Rising pollution, declining fossil fuels, environmental concerns, economic development, climate change, the food crisis, and fuel price fluctuations have posed serious challenges for energy planning and management [1]. In recent years, on the one hand, issues such as energy security and countries' dependence on fossil fuels that end one day, and on the other hand, crises caused by environmental pollution have shifted countries to alternative sources that address the above two challenges [2]. Experts have examined alternative sources that are both renewable and cleaner. Considering that the transportation sector has a great impact on environmental pollution, finding alternative sources in this sector can greatly help reduce environmental pollution [3].

Experts believe that using clean energy such as solar energy, wind, biomass, etc., instead of fossil fuels, will prevent environmental pollution and its dangers [4]. Expert research shows that biofuels, which can be supplied from various sources, can be economically and environmentally suitable alternatives to fossil fuels [5]. Biofuels can be produced from biomass, including agricultural, household, commercial and industrial waste, crops and natural biomass. Bioethanol and biodiesel can be used as liquid biofuels as fuel for vehicles or additives to petroleum-based fuels [6]. Biodiesel is a type of biofuel that can be successfully combined with diesel earned from fossil fuels at different percentages for transportation [7]. Jatropha is a promising source of biodiesel production that has received much attention due to its high oil content for biodiesel production, drought tolerance and water scarcity, soil reclamation, desert reduction, rural development, and environmental benefits [8].

Despite much attention to the biofuel supply chain in recent years, few papers have addressed the drop-in property of advanced hydrocarbon biofuel. The US Department of Energy in a study has addressed the issue of integrating a hydrocarbon biofuel supply chain with existing oil supply chain production and distribution infrastructure. They show three connection points for these two chains. First, after preprocessing the biomass and liquefying it, they combine it with the crude oil and lead it to the distillation towers. The second is for the semi-finished material to go to upgrade units for further processing, and the third is for the finished fuel to come to a warehouse or distribution point for petroleum products to use the existing distribution capacity. This eliminates the need of building many facilities in the biofuel supply chain and reduces many costs [9]. Therefore, some

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papers have studied how to integrate these two supply chains. Huber and Corma [10] studied biomass conversion techniques for biofuels through existing oil refineries. They concluded that there are three techniques for this: catalytic cracking, hydro-treating, and hydrocracking. In order to lower the cost of advanced hydrocarbon biofuels to a level comparable to conventional fuels, a sophisticated supply chain model, which considers designing, logistics, and planning decisions, is urgently needed to take the advantage of the existing petroleum refinery infrastructures.

This paper proposes a multi-objective Mixed Integer Linear Programming (MILP) model to design an integrated biodiesel and gas-oil supply chain. The proposed model considers all parts of both chains from harvesting sites of the biodiesel supply chain and oil fields of the gas-oil supply chain to the final customers. Besides maximizing profits as an economic goal, the proposed model also minimizes the emission of carbon dioxide as an environmental goal. Jatropha is considered a feedstock in the biodiesel supply chain due to its proper biodiesel production characteristics, which has already been pointed out. According to [11] and its case study that was done for Iran, Jatropha is more viable than bio-wastes. Also, due to the model's reduced complexity and its solution time, only Jatropha is considered feedstock. This model can be used in many strategic and tactical decisions such as location, allocation, capacity expansion, production planning, and inventory management. This paper has been used for a genuine case in Iran for the 20-year planning horizon.

The rest of this article is as follows. The literature review is presented in Section 2. The concerned problem is described in Section 3. The symbols used in the model and the developed model are presented in Section 4. The solution method used is described in Section 5. The case study and its relevant results are described in Section 6. Finally, the results and some directions for future research are presented in Section 7.

2 Literature review

The issue of designing a network of oil supply chains and biofuels has been the focus of many researchers due to the inclusion of various strategic, tactical, and operational decisions. Responses to all decisions such as location, allocation, capacity determination, capacity expansion, technology selection, production planning, inventory management, and so forth can be obtained as a chain network design model. Numerous papers have examined the supply chain of crude oil and petroleum products and biofuels to provide energy with maximum profit and minimum environmental pollution. In papers related to the oil supply chain and petroleum products, part or all of the supply chain is optimized. Papers optimizing the supply chain by considering biomass generation as raw material are also discussed in papers on the biofuel supply chain.

To better understand the studies conducted on the oil supply chain and its derivatives and the biofuel supply chain, we would separately investigate the papers and studies conducted on these two issues. Table 1 shows the papers' classification on the oil supply chain and its derivatives and on the biofuel supply chain. The upper half of the table shows the papers on oil, and the lower half shows the ones on biofuels.

2.1 Literature review of oil and petroleum products supply chain

The oil supply chain and its derivatives have always attracted researchers' attention due to their breadth, importance and attractiveness. The studies carried out in this field are very extensive. Therefore, in this paper, only the studies conducted on designing the oil supply chain network and its derivatives are discussed.

As shown in Table 1, the papers' structure on the oil supply chain and its derivatives can include upstream parts such as oil fields and crude oil storage centers and intermediate parts such as refineries and product storage centers and downstream parts such as distribution centers and customer types. Much research has been done on the downstream and midstream of the oil supply chain. Fernandes *et al.* [12] consider a multi-level, multi-product and multi-transportation downstream Petroleum Supply Chain (PSC) network. In another paper, they [13] developed their work with a dynamic MILP model for collaborative design and tactical planning. Guajardo *et al.* [14] presented a model for a company's downstream oil supply chain and determined the optimal plan for it. Fiorencio *et al.* [15] presented a MILP-based Decision Support System (DSS) that enables strategic planning of the oil supply chain. This model is used for studies evaluating investment options for a logistics infrastructure. Kazemi and Szmerekovsky [16] presented a MILP model for a multi-product, multi-level downstream oil supply chain network that minimizes costs. Their model addresses multi-modal transportation planning in strategic supply chain design. Ghezavati *et al.* [17] designed the downstream part of the PSC. They demonstrated 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. Öztürkoğlu and Lawal [18] developed a single-period and single-product deterministic mathematical model and analyzed scenarios such as breakdowns in pipeline connections. Ghaithan *et al.* [19] have presented an integrated multi-objective model for mid-term tactical decision-making for the downstream part of the oil and gas supply chain. Lima *et al.* [20] presented a multi-stage stochastic programming to solve the refined product distribution problem optimally. Wang *et al.* [21] have presented a MILP model for optimizing the downstream segment of the oil supply chain to plan new pipelines.

Many researchers have studied the upstream oil supply chain, and some by considering it as integrated. Leiras *et al.* [22] address integration and coordination under uncertainty the tactical and operational levels. Spatial integration is examined the tactical level, while temporal integration is examined by the interaction between tactical and operational levels. Gamari and Sahebi [23] presented a multi-objective mathematical model for stochastic lot-sizing in the petrochemical supply chain, considering uncertainty.

Table 1. An overview of some papers in oil supply chain and its derivatives and biofuel supply chain.

Reference	Structure														Decision level							Modelling									
															Strategic			Tactical				Modelling approach				Objective function					
	Oil field	Crude oil storage center	Distillation unit	Refinery production unit	Upgrading unit in oil supply chain	Product storage center	Export terminal	Harvesting center	Collection center	Pre-processing unit	Upgrading unit in biofuel supply chain	Bio-refinery	Distribution center	Customer	Location	Capacity	Technology	Allocation	Production planning	Inventory planning	Transportation	LP	MILP	NLP	MINLP	Single objective	Multi objective	Economic	Environmental	Social	Others
[19]				✓		✓	✓						✓	✓				✓	✓	✓		✓					✓	✓			✓
[21]				✓		✓							✓	✓	✓			✓					✓			✓		✓			
[20]				✓		✓	✓						✓	✓				✓	✓	✓	✓	✓				✓		✓			
[24]	✓	✓		✓		✓	✓						✓	✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			
[26]	✓						✓							✓	✓			✓	✓		✓		✓			✓		✓			
[16]				✓		✓							✓	✓	✓	✓		✓			✓		✓			✓		✓			
[27]	✓			✓		✓	✓						✓		✓	✓	✓	✓	✓					✓			✓	✓	✓		
[12]				✓		✓							✓	✓	✓	✓		✓	✓		✓		✓			✓		✓			
[30]	✓			✓		✓							✓	✓	✓	✓		✓		✓			✓			✓		✓			
[22]	✓			✓		✓	✓						✓	✓				✓	✓	✓		✓				✓		✓			
[14]				✓		✓							✓	✓				✓	✓	✓		✓					✓	✓			
[17]				✓		✓							✓	✓	✓	✓		✓	✓		✓		✓			✓		✓			
[13]				✓		✓							✓	✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			
[32]	✓			✓										✓				✓	✓	✓		✓				✓		✓			
[15]				✓		✓	✓						✓		✓	✓		✓	✓	✓			✓			✓		✓			
[31]	✓	✓													✓	✓		✓	✓				✓			✓		✓			
[25]	✓						✓							✓	✓			✓	✓				✓			✓		✓			
[18]				✓		✓	✓						✓	✓		✓		✓					✓			✓		✓			
[28]	✓			✓		✓	✓						✓		✓	✓	✓	✓	✓		✓				✓	✓		✓			
[45]								✓		✓		✓		✓	✓	✓		✓					✓				✓	✓	✓	✓	
[42]								✓	✓			✓		✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			
[33]								✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓		✓			
[48]								✓				✓		✓	✓	✓	✓	✓	✓	✓	✓		✓			✓		✓			
[43]								✓	✓			✓		✓				✓	✓		✓	✓	✓			✓		✓			
[40]								✓		✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			✓					✓
[44]								✓				✓		✓	✓	✓	✓	✓	✓	✓			✓			✓		✓			
[38]								✓	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓		✓			✓		✓			
[39]								✓	✓			✓		✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			
[50]								✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓				✓	✓	✓	✓	
[51]								✓				✓		✓	✓	✓		✓	✓		✓		✓			✓		✓			
[41]								✓				✓		✓	✓	✓	✓	✓	✓		✓		✓				✓	✓	✓	✓	
[34]								✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓				✓	✓	✓		
[46]								✓				✓		✓	✓	✓		✓	✓	✓			✓			✓		✓			
[33]								✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓		✓			
[1]								✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			
[35]								✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			
[53]		✓			✓			✓		✓		✓		✓	✓	✓	✓	✓	✓		✓		✓			✓		✓			
[54]		✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓		✓			
[55]		✓	✓		✓	✓		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓			✓		✓			
Current research	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓				✓	✓	✓		

In a study, Nasab and Amin-Naseri [24] investigated a multi-level, multi-modal transportation and multi-period integrated oil supply chain to obtain a global optimal solution. They simultaneously considered both the construction and capacity expansion of the facilities and the pipeline route. Jabbarzadeh *et al.* [25] presented a multi-period MILP mathematical model for designing the oil supply chain network. Farahani and Rahmani [26] introduced a MILP model to maximize the net present value of a crude oil network. The effect of gas injection and swap simultaneously is considered in the proposed model. Azadeh *et al.* [27] presented a multi-objective mathematical model for integrating the upstream and middle sectors of the crude oil supply chain of environmental indicators. In this paper, an algorithm based on the Multi-Objective Evolutionary Algorithm Based on Decomposition (MOEA-D) approach is used to solve the proposed nonlinear Mixed Integer Programming (MINLP) model. Azadeh *et al.* [28] also presented another paper that year that simultaneously focuses on the upstream and downstream sectors of the crude oil supply chain. This paper also puts into consideration the simultaneous development of the oil field and the planning of the transformation.

As shown in Table 1, decision levels can vary from paper to paper. Among the most important decisions are location, capacity determination or expansion, technology selection, allocation, production planning, inventory planning, and transportation-related decisions. Fernandes *et al.* [12], through developing MILP, strategically designed and planned the PSC downstream network and determine the optimal locations of depots, optimal capacities, modes of transport and long-term planning. MILP maximizes profit of petroleum companies and is tested with a real PSC network in Portugal. Guajardo *et al.* [14] addressed tactical issues related to decision making in production, distribution to customers, and inventory. The decision levels of other papers are also listed in Table 1.

To model, papers can be classified into different categories. The major problems are actually MINLP, but the mathematical models are in the LP, MILP, NLP, and MINLP types. Papers can also be classified into single-objective and multi-objective in terms of the type of objective function. Most multi-objective models in this area have used economic and environmental functions. Zhou *et al.* [29] presented a multi-objective MILP model for minimizing total economic costs and CO_2 gas emissions simultaneously. They identified the Pareto boundary for solving the multi-objective model and examined it in a real-world example. Also Ghaithan *et al.* [19] have presented an integrated multi-objective model. The objectives of this paper are: minimize total costs, maximize total revenue, and maximize service level. Uncertainty in parameters is another important factor that should be considered in the classification of papers. In a general division, the approach to dealing with uncertainty in papers can be divided into three categories: fuzzy, robust, and stochastic. For example, Oliveira *et al.* [30] presented a two-stage stochastic programming model for the petroleum products supply chain. They also used the development of stochastic Benders decomposition method to solve. Gupta and Grossmann [31] presented a multi-stage stochastic programming model for planning the offshore oil and gas fields' infrastructure. They considered endogenous uncertainties and complex fiscal rules into their planning model. Jabbarzadeh *et al.* [25] investigated uncertain parameters via fuzzy theory. Lima *et al.* [20] presented a multi-stage stochastic programming model. To investigate the uncertainty in oil price and demand, they used time series as well as scenario tree analyses. They also used Auto-Regressive Integrated Moving Average (ARIMA) method for time series analysis and a scenario reduction method to compress the problem dimensions. Beiranvand *et al.* [32] proposed a robust optimization model to consider demand and price uncertainties.

2.2 Literature review of biofuel supply chain

Although biofuel supply chain studies are not as old as oil supply chain studies, they have attracted the attention of many researchers in recent years. Crises caused by countries' dependence on oil have drawn the attention of researchers to alternative sources, the most important of which are biofuels. Features of biofuel supply chain papers can also be included in Table 1. The structures of the supply chain network, considered in most papers in this field, are similar, and in some cases, there is a slight difference. The feedstock considered in the biofuel supply chain papers can vary. Most papers consider the second generation of feedstock. Some papers also consider a combination of generations. Babazadeh [33] presented a multi-period and multi-product biodiesel supply chain network design model. He is considering Jatropha seeds and waste cooking oil to produce second-generation biodiesel. Babazadeh *et al.* [34] presented a possible multi-objective programming model for the design of the second generation biodiesel supply chain network under risk conditions. This paper presents a planning method for risk reduction based on uncertainty. Ezzati *et al.* [35] designed the biodiesel supply chain network with Jatropha, waste cooking oil, and microalgae as feed stocks. They offered a multi-period, multi-product, multi-mode MILP model that integrates all levels of the chain. Mahjoub *et al.* [11] developed a multi-period multi-objective MILP model that designs the second/third generation biofuel supply chain. They studied three types of biomass simultaneously as a feedstock for production and used an augmented ε-constraint approach to solve it. Kheybari *et al.* [36] focused on identifying the best location for the production of bioethanol. They proposed an evaluation framework that based on the three dimensions of sustainability. They applied the Best-Worst Method (BWM) in their paper. Kang *et al.* [37] proposed a three-step model for designing a biofuel supply chain from microalgae. The first stage is the design of economic decisions and analyses. The second stage is selecting candidate locations based on GIS, and the third stage is the mathematical optimization.

Biofuel papers, as shown in Table 1, can help make various decisions at different levels. Lin *et al.* [38] presented a MILP model for optimizing strategic and tactical decisions. This model covers all activities from harvesting to distribution. In some papers, issues such as seasonal feedstock are considered in the design of biofuel supply chain networks.

Xie *et al.* [39] proposed a multi-stage MILP model for the cellulosic biofuel supply chain. This paper deals with the feedstock's seasonality. Santibañez-Aguilar *et al.* [40] presented a dynamic optimization model for optimal supply chain planning. They considered the seasonality of biomass cultivation in their study.

Papers on biofuels can also single-objective or multi-objective. The objectives of these papers are mainly economic, environmental, and social. Mousavi Ahranjani *et al.* [41] presented a model that simultaneously considers economic, environmental, and social objectives. Also, Fattahi and Govindan [42] considered environmental and social aspects. Ghani *et al.* [43] examined the impact of incentives on one side and the greenhouse gas emissions penalty. On the other, it made farmers refrain from burning biomass residues and provide opportunities to convert these materials into biofuels. As a result, the costs and emissions of greenhouse gases are reduced.

Another feature of papers in this field is the certainty or uncertainty in network design. Papers that consider uncertainty in parameters are generally classified into three categories: fuzzy, robust, and stochastic. Azadeh *et al.* [44] presented a multi-period stochastic linear programming model that maximizes profits and then analyzed the results. Zhang and Jiang [45] designed biofuel supply chain based on waste cooking oil at strategic and tactical levels. They introduced a multi-objective MILP model with a robust approach. Mohseni *et al.* [46] presented a two-stage model for designing and planning a biodiesel supply chain from microalgae. They used GIS and AHP to determine potential locations. They used a robust MILP model to optimize in uncertainty. Gilani *et al.* [47] proposed a three-phase robust optimization model for network design of supply chain to produce bioethanol from sugarcane. They employed fuzzy integrated data envelopment analysis method to select suitable cultivation lands as supply potential points. Their model performance has been illustrated through a case study in Iran. Bairamzadeh *et al.* [48] presented a MILP model for determining the strategic and tactical decisions of the bioethanol lignocellulosic supply chain. A hybrid robust optimization model has been used to consider the uncertainties. Ghelichi *et al.* [1] presented a two-stage stochastic programming model for designing an integrated green biodiesel supply chain from Jatropha seeds. In their multi-product, multi-period MILP model, they developed a two-stage scenario-based stochastic programming approach. Shavazipour *et al.* [49] presented a two-stage scenario-based multi-objective optimization methodology. They considered three objectives in their problem under uncertainty of six parameters. A case study of South African sugarcane industry utilized to examine the proposed model. Mousavi Ahranjani *et al.* [41] presented a hybrid multi-objective robust possibilistic programming model for designing and planning a multi-period biofuel supply chain network under uncertainty. Fattahi and Govindan [42] presented a multi-stage stochastic programming model for biofuel supply chain design and planning. Ghaderi *et al.* [50] presented a multi-objective robust possibilistic programming model for designing a sustainable bioethanol supply chain network. Babazadeh *et al.* [51] presented a possibilistic programming model for designing the second-generation biodiesel supply chain network under uncertainty, in which case Jatropha seeds and waste cooking oil are considered the raw material of biodiesel. They also used a benders-local branching algorithm to solve their model. Razm *et al.* [52] made a redesign of the biomass supply network by considering price changes as a decision variable. They examined demand and exchange rates in three different scenarios.

None of the above papers have considered the use of oil network infrastructure to produce biofuels. Tong *et al.* [53] optimized and strategically planned the integrated hydrocarbon biofuel system and oil supply chain under uncertainty. This paper proposes a two-stage stochastic MILP model for optimal design and strategic planning of hydrocarbon and petroleum fuels using uncertainty. Tong *et al.* [54] designed the optimal design of an advanced integrated hydrocarbon biofuel supply chain with existing oil refineries and analyzed the three points of connection of the biofuel supply chain with oil refineries. They also provided a multi-period fuzzy MILP model to consider uncertainties. In another paper in the same year, Tong *et al.* [55] designed an optimal biofuel supply chain for advanced integrated hydrocarbons with existing oil refineries and identified an integration strategy using the robust optimization approach.

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

- Elaborating a novel sustainable planning model to design a fuel and biofuel supply chain network to mitigate CO_2 emissions and improve economic performance.
- Addressing a comprehensive diesel supply chain including upstream, midstream, and downstream entities.
- Developing a bi-objective model to integrate gas-oil and biodiesel supply chain network design.
- Simultaneous consideration of environmental pollution caused by transportation within the supply chain and reduction of pollution due to the use of biodiesel instead of diesel.
- Applying the developed bi-objective mathematical model to a real case study.

3 Problem definition

The issue under discussion in this study is the design of an integrated gas-oil and biodiesel supply chain network that considers all parts of both chains, from harvesting sites in the biodiesel supply chain and oil fields in the gas-oil supply chain to final products for the customers. The issue discussed in this study is examined through a deterministic multi-objective MILP model so that in addition to maximizing profits as an economic goal, it also minimizes the emission of carbon dioxide as an environmental goal.

According to [56], the harvested biomass feed stocks can either be sent to integrated bio-refineries for direct production, or undergo a two-stage conversion process, namely pre-conversion and upgrading. Pre-conversion stage

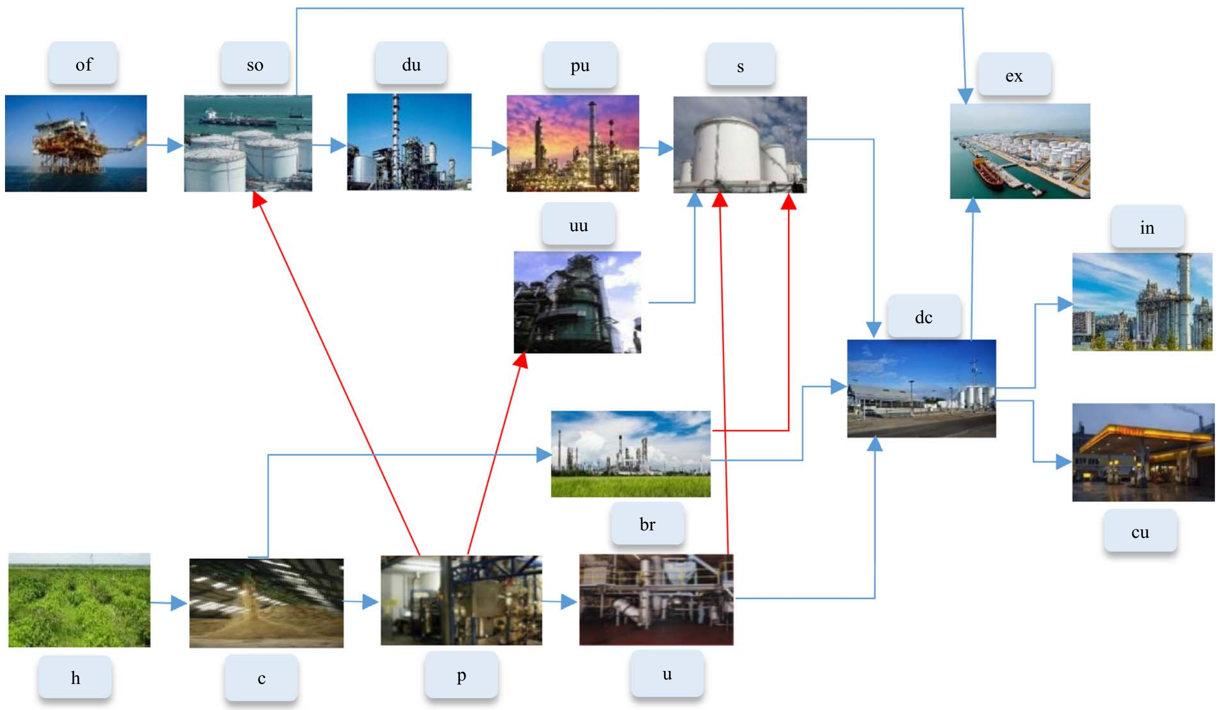

Fig. 1. The structure of the integrated gas-oil and biodiesel supply chain network studied in this paper (of: oil fields, so: crude oil storage, du: crude oil distillation centers, pu: refinery production units, uu: upgrading units in the gas-oil supply chain, s: fuel storage centers, h: Jatropha harvesting centers, c: Jatropha collection centers, p: pre-processing units, u: upgrading units in the biodiesel supply chain, br: bio-refineries, dc: distribution centers, ex: export centers, in: industries, cu: customers).

converts biomass into bio-intermediates (*e.g.*, bio-oil and bio-slurry) that is economical and efficient for transportation, whereas upgrading stage upgrades the bio-intermediates into final products [57]. Crude oil flows from oil fields to crude oil storage facilities, some of which are exported. In the biodiesel supply chain, Jatropha can be transferred from harvesting sites to collection centers and pre-processing centers and biodiesel refineries. On the one hand, after pre-processing in the biomass supply chain, the bio-slurry enters the crude oil storage. The inflows to the crude oil storage centers enter the distillation towers. After separation, diesel is obtained in distillation towers, which the consumer cannot use according to the standards, and the final processing must be done in the production units. Bio-slurry and bio-oil were obtained in pre-processing units, where bio-oils directly enter the upgrading units in oil refineries. On the other hand, the materials that come out of the pre-processing units can be turned into the final product in the upgrading units that are in the biofuel chain. Also, from biomass collection centers, they can be transferred directly to biodiesel refineries where all processes can be done and the final product can be obtained. The final product obtained from the upgrade units in the oil supply chain as well as the production units enters the product storage centers. There are two ways to get the final products from biodiesel refineries and upgrade centers in the biofuel supply chain: either entering the products' storage centers and sending them to the distribution centers after mixing or sending them directly to the distribution centers where they can be mixed. Finally, the final product is sent from distribution centers to customer centers, industry and export centers. Figure 1 shows the schematic of the network examined in this paper: Oil fields, crude oil storage centers, distillation towers, upgrading units in the diesel supply chain, refinery production units, product storage centers, export terminals, distribution centers, Jatropha farms, Jatropha collection centers, pre-processing units, upgrading units in the biodiesel supply chain, and bio-refineries, each has a certain level of capacity. Except for the refinery production units, other cases have a fixed capacity. Refinery production units can increase capacity to a certain extent. There is infinite capacity for the means of transport and only one mode of transport is considered. The model will determine the construction of upgrading units in the diesel supply chain, Jatropha harvesting sites, Jatropha collection centers, pre-processing units, upgrading units in the biodiesel supply chain, bio-refineries and distribution centers.

For crude oil storage centers, product storage centers and Jatropha storage centers, inventory costs are considered. In the upgrading units in the diesel supply chain, refinery production units, pre-processing units, upgrading units in the biodiesel supply chain and bio-refineries production yield. The environmental goal function considers two issues. The first is to minimize the emissions of carbon dioxide from transportation in the supply chain network, and the second is to maximize future savings from using biodiesel instead of diesel. These two issues are simultaneously considered in the environmental objective function. The problem is considered for a 7-year planning horizon. However, to reduce the computational complexity of the problem, a time is considered each year. The main decisions made by the model: location, allocation, capacity expansion, inventory management, and production planning.

4 Model formulation

The indices, parameters, and variables of the proposed model are defined in the Table A.1 (Appendix).

In the current study, a MILP model with two objective functions is proposed. The first objective function is presented in equation (1) which maximizes the profit using net present value method. The second objective function is presented in equation (9) which minimizes the adverse environmental effects in a certain way that will be explained.

4.1 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,

$$\max \text{profit} = \text{income} - \text{cost}. \quad (1)$$

The net present value of the income is obtained by converting the income of each period to the present value in accordance with equation (2),

$$\text{income} = \sum_{t=1}^{T} (1+dr)^{-(t-1)} \cdot \text{inc}_t. \quad (2)$$

The income of each period in accordance with equation (3) is obtained from the total income from the sale of the product to local customers, industries and export centers, as well as the sale of crude oil to export centers,

$$\text{inc}_t = \sum_{ex}\sum_{so} q_t^{so,ex} \cdot \text{oex}_t + \sum_{ex}\sum_{dc} q_t^{dc,ex} \cdot \text{prex}_t + \sum_{in}\sum_{dc} q_t^{dc,in} \cdot \text{prin}_t + \sum_{cu}\sum_{dc} q_t^{dc,cu} \cdot \text{prcu}_t \quad \forall t. \quad (3)$$

Similar to the present value of incomes, to obtain the present value of the costs, we convert the sum of the costs of each period to the present value in accordance with equation (4),

$$\cos t = \sum_{t=1}^{T} (1+dr)^{-(t-1)} \cdot (\text{cinv}_t + \text{cop}_t + \text{ctr}_t + \text{ch}_t). \quad (4)$$

According to equation (4), costs comprise several elements: investment costs, operating costs, transportation costs, and inventory holding costs. Investment costs in accordance with equation (5) are obtained from the costs of building potential centers and the costs of increasing the capacity of refinery production units,

$$\text{cinv}_t = \sum_{uu} \text{cc}_t^{uu} \cdot x_{uu,t} + \sum_{h} \text{cc}_t^{h} \cdot x_{h,t} \cdot \text{ca}_h + \sum_{c} \text{cc}_t^{c} \cdot x_{c,t} + \sum_{p} \text{cc}_t^{p} \cdot x_{p,t} + \sum_{u} \text{cc}_t^{u} \cdot x_{u,t} + \sum_{dc} \text{cc}_t^{dc} \cdot x_{dc,t} + \sum_{br} \text{cc}_t^{br} \cdot x_{br,t} + \sum_{pu} \text{cc}_t^{pu} \cdot l_t^{pu} \quad \forall t. \quad (5)$$

The second cost element is operating costs, which are obtained in accordance with equation (6). In units where processing is performed, we have operating costs,

$$\text{cop}_t = \sum_{du}\sum_{so} \text{cprdu}_t \cdot q_t^{so,du} + \sum_{uu}\sum_{du} \text{cpruu}_t \cdot q_t^{du,uu} + \sum_{pu}\sum_{du} \text{cprpu}_t \cdot q_t^{pu,du} + \sum_{p}\sum_{c} \text{cprp}_t \cdot q_t^{c,p} + \sum_{u}\sum_{p} \text{cpru}_t \cdot q_t^{p,u} + \sum_{br}\sum_{c} \text{cprbr}_t \cdot q_t^{c,br}. \quad (6)$$

The third cost element is transportation costs, which are obtained in accordance with equation (7). Transportation costs are considered between all network units where raw materials, intermediate products and final products are transported.

See Equation (7) bottom of the page

The fourth cost element is inventory holding costs, which are obtained in accordance with equation (8). This

$$\begin{aligned}\text{ctr}_t = \text{chan} \cdot \Bigg(& \sum_{so}\sum_{of} \text{ctr}_{of,so} \cdot q_t^{of,so} + \sum_{ex}\sum_{so} \text{ctr}_{so,ex} \cdot q_t^{so,ex} + \sum_{du}\sum_{so} \text{ctr}_{so,du} \cdot q_t^{so,du} + \sum_{pu}\sum_{du} \text{ctr}_{du,pu} \cdot q_t^{du,pu} \\ & + \sum_{uu}\sum_{du} \text{ctr}_{du,uu} \cdot q_t^{du,uu} + \sum_{s}\sum_{pu} \text{ctr}_{pu,s} \cdot q_t^{pu,s} + \sum_{s}\sum_{uu} \text{ctr}_{uu,s} \cdot q_t^{uu,s} + \sum_{dc}\sum_{s} \text{ctr}_{s,dc} \cdot q_t^{s,dc} + \sum_{ex}\sum_{dc} \text{ctr}_{dc,ex} \\ & \cdot q_t^{dc,ex} + \sum_{cu}\sum_{dc} \text{ctr}_{dc,cu} \cdot q_t^{dc,cu} + \sum_{in}\sum_{dc} \text{ctr}_{dc,in} \cdot q_t^{dc,in} + \sum_{c}\sum_{h} \text{ctr}_{h,c} \cdot q_t^{h,c} + \sum_{p}\sum_{c} \text{ctr}_{c,p} \cdot q_t^{c,p} \\ & + \sum_{br}\sum_{c} \text{ctr}_{c,br} \cdot q_t^{c,br} + \sum_{u}\sum_{p} \text{ctr}_{p,u} \cdot q_t^{p,u} + \sum_{uu}\sum_{p} \text{ctr}_{p,uu} \cdot q_t^{p,uu} + \sum_{so}\sum_{p} \text{ctr}_{p,so} \cdot q_t^{p,so} + \sum_{s}\sum_{br} \text{ctr}_{br,s} \cdot q_t^{br,s} \\ & + \sum_{dc}\sum_{br} \text{ctr}_{br,dc} \cdot q_t^{br,dc} + \sum_{s}\sum_{u} \text{ctr}_{u,s} \cdot q_t^{u,s} + \sum_{dc}\sum_{u} \text{ctr}_{u,dc} \cdot q_t^{u,dc} \Bigg) \quad \forall t. \quad (7)\end{aligned}$$

$$\mathrm{envt}_t = \mathrm{enchan} \cdot \Bigg(\sum_{of} \sum_{so} \mathrm{entr} \cdot q_t^{of,so} \cdot d^{of,so} + \sum_{so} \sum_{ex} \mathrm{entr} \cdot q_t^{so,ex} \cdot d^{so,ex} + \sum_{so} \sum_{du} \mathrm{entr} \cdot q_t^{so,du} \cdot d^{so,du}$$
$$+ \sum_{du} \sum_{pu} \mathrm{entr} \cdot q_t^{du,pu} \cdot d^{du,pu} + \sum_{pu} \sum_{s} \mathrm{entr} \cdot q_t^{pu,s} \cdot d^{pu,s} + \sum_{uu} \sum_{s} \mathrm{entr} \cdot q_t^{uu,s} \cdot d^{uu,s} + \sum_{s} \sum_{dc} \mathrm{entr} \cdot q_t^{s,dc} \cdot d^{s,dc}$$
$$+ \sum_{dc} \sum_{ex} \mathrm{entr} \cdot q_t^{dc,ex} \cdot d^{dc,ex} + \sum_{dc} \sum_{cu} \mathrm{entr} \cdot q_t^{dc,cu} \cdot d^{dc,cu} + \sum_{dc} \sum_{in} \mathrm{entr} \cdot q_t^{dc,in} \cdot d^{dc,in} + \sum_{h} \sum_{c} \mathrm{entr} \cdot q_t^{h,c} \cdot d^{h,c} \quad \forall t.$$
$$+ \sum_{c} \sum_{p} \mathrm{entr} \cdot q_t^{c,p} \cdot d^{c,p} + \sum_{c} \sum_{br} \mathrm{entr} \cdot q_t^{c,br} \cdot d^{c,br} + \sum_{p} \sum_{u} \mathrm{entr} \cdot q_t^{p,u} \cdot d^{p,u} + \sum_{p} \sum_{uu} \mathrm{entr} \cdot q_t^{p,uu} \cdot d^{p,uu}$$
$$+ \sum_{p} \sum_{so} \mathrm{entr} \cdot q_t^{p,so} \cdot d^{p,so} + \sum_{br} \sum_{s} \mathrm{entr} \cdot q_t^{br,s} \cdot d^{br,s} + \sum_{br} \sum_{dc} \mathrm{entr} \cdot q_t^{br,dc} \cdot d^{br,dc} + \sum_{u} \sum_{s} \mathrm{entr} \cdot q_t^{u,s} \cdot d^{u,s}$$
$$+ \sum_{u} \sum_{dc} \mathrm{entr} \cdot q_t^{u,dc} \cdot d^{u,dc} \Bigg) \tag{10}$$

cost is calculated for Jatropha storage units, crude oil storage units, and final product storage units,

$$\mathrm{ch}_t = \sum_{so} \mathrm{inv}_t^{so} \cdot \mathrm{ho}_t^{so} + \sum_{s} \mathrm{inv}_t^{s} \cdot \mathrm{ho}_t^{s} + \sum_{c} \mathrm{inv}_t^{c} \cdot \mathrm{ho}_t^{c} \quad \forall t. \tag{8}$$

4.2 Environmental objective function

In this paper, the environmental objective function is obtained from the difference between the two equations. Using the first equation, the goal is to reduce the amount of carbon dioxide emissions caused by transportation on the network. With the help of the second equation, the goal is to increase the savings in carbon dioxide emissions by using biodiesel instead of gas-oil. This is shown in equations (9)–(11),

$$\sum_{t=1}^{T} (\mathrm{envt}_t - \mathrm{envi}_t). \tag{9}$$

In equation (10), according to the amount of carbon dioxide emissions per unit distance due to network transport, the amount of carbon dioxide produced by transportation throughout the network is obtained,

See Equation (10) top of the page

In equation (11), according to the amount of biodiesel produced from different units of the supply chain network and the coefficient indicating a decrease in carbon dioxide emissions due to biodiesel instead of gas-oil, the amount of carbon dioxide emission reduction is obtained,

See Equation (11) bottom of the page

4.3 Model constraints

Material balance constraint: equations (12)–(21) show the balance between inputs and outputs to network elements. In some elements, due to the loss of inputs, the output value is less than the input, which is formulated by considering the element's efficiency factor,

$$\sum_{of} q_t^{of,so} + \sum_{p} q_t^{p,so} = \sum_{du} q_t^{so,du} + \sum_{ex} q_t^{so,ex} + plus_t^{so} \quad \forall so,\ t, \tag{12}$$

$$\sum_{so} q_t^{so,du} = \sum_{pu} q_t^{du,pu} \quad \forall du,\ t, \tag{13}$$

$$(1 - \mathrm{alpha1}) \cdot \sum_{p} q_t^{p,uu} = \sum_{s} q_t^{uu,s} \quad \forall uu,\ t, \tag{14}$$

$$(1 - \mathrm{alpha2}) \cdot \sum_{du} q_t^{du,pu} = \sum_{s} q_t^{pu,s} \quad \forall pu,\ t, \tag{15}$$

$$\sum_{uu} q_t^{uu,s} + \sum_{br} q_t^{br,s} + \sum_{u} q_t^{u,s} + \sum_{pu} q_t^{pu,s} = \sum_{dc} q_t^{s,dc} + plus_t^{s} \quad \forall s,\ t, \tag{16}$$

$$\sum_{h} q_t^{h,c} = \sum_{p} q_t^{c,p} + \sum_{br} q_t^{c,br} + \mathrm{plus}_t^{c} \quad \forall c,\ t, \tag{17}$$

$$(1 - \mathrm{alpha3}) \cdot \sum_{c} q_t^{c,p} = \sum_{so} q_t^{p,so} + \sum_{u} q_t^{p,u} + \sum_{uu} q_t^{p,uu} \quad \forall p,\ t, \tag{18}$$

$$(1 - \mathrm{alpha4}) \cdot \sum_{c} q_t^{c,br} = \sum_{s} q_t^{br,s} + \sum_{dc} q_t^{br,dc} \mathrm{v}\forall\ br,\ t, \tag{19}$$

$$\mathrm{envi}_t = \mathrm{echan} \cdot \left(\sum_{uu} \sum_{s} q_t^{uu,s} + \sum_{br} \sum_{s} q_t^{br,s} + \sum_{br} \sum_{dc} q_t^{br,dc} + \sum_{u} \sum_{s} q_t^{u,s} + \sum_{u} \sum_{dc} q_t^{u,dc} \right) \quad \forall t. \tag{11}$$

$$(1-\text{alpha5})\cdot\sum_{p} q_t^{p,u} = \sum_{s} q_t^{u,s} + \sum_{dc} q_t^{u,dc} \quad \forall\, u,\ t. \tag{20}$$

Demand constraint: equations (22)–(25) indicate demand satisfaction. Equation (22) shows the satisfaction of crude oil demand for export terminals, equation (23) shows satisfaction of product demand for export terminals, equation (24) shows satisfaction of product demand for local customers and equation (25) shows satisfaction of product demand for industries,

$$\sum_{u} q_t^{u,dc} + \sum_{br} q_t^{br,dc} + \sum_{s} q_t^{s,dc} = \sum_{ex} q_t^{dc,ex} + \sum_{in} q_t^{dc,in} + \sum_{cu} q_t^{dc,cu} \qquad \forall\, dc,\ t, \tag{21}$$

$$\sum_{so} q_t^{so,ex} \geq dex_t^{ex} \qquad \forall\, ex,\ t, \tag{22}$$

$$\sum_{dc} q_t^{dc,ex} \geq dpr_t^{ex} \qquad \forall\, ex,\ t, \tag{23}$$

$$\sum_{dc} q_t^{dc,cu} \geq dpr_t^{cu} \qquad \forall\, cu,\ t, \tag{24}$$

$$\sum_{dc} q_t^{dc,in} \geq dpr_t^{in} \qquad \forall\, in,\ t. \tag{25}$$

Capacity constraint: equations (26)–(39) are related to considering network elements' capacity for inputs and outputs. For potential points, the availability of that location is to be first checked, and if available, the capacity of that location to enter and exit the stream would be considered. In the case of refinery production units, the capacity varies according to the possibility of increasing production capacity, which is shown in equations (30) and (31),

$$\sum_{so} q_t^{of,so} \leq ca_{of} \qquad \forall\, of,\ t, \tag{26}$$

$$\sum_{of} q_t^{of,so} + \sum_{p} q_t^{p,so} \leq ca_{so} \qquad \forall\, so,\ t, \tag{27}$$

$$\sum_{so} q_t^{so,du} \leq ca_{du} \qquad \forall\, du,\ t, \tag{28}$$

$$\sum_{p} q_t^{p,uu} \leq ca_{uu}\cdot y_{uu,t} \qquad \forall\, uu,\ t, \tag{29}$$

$$\sum_{du} q_t^{du,pu} \leq ca_t^{pu} \qquad \forall\, pu,\ t, \tag{30}$$

$$\text{ca}_{t+1}^{pu} \leq \text{ca}_t^{pu} + l_{t+1}^{pu} \qquad \forall\, pu,\ t, \tag{31}$$

$$\sum_{uu} q_t^{uu,s} + \sum_{br} q_t^{br,s} + \sum_{pu} q_t^{pu,s} + \sum_{u} q_t^{u,s} \leq \text{ca}_s \qquad \forall\, s,\ t, \tag{32}$$

$$\sum_{so} q_t^{so,ex} + \sum_{dc} q_t^{dc,ex} \leq \text{ca}_{ex} \qquad \forall\, ex,\ t, \tag{33}$$

$$\sum_{c} q_t^{h,c} \leq \text{ca}_h\cdot y_{h,t} \qquad \forall\, h,\ t, \tag{34}$$

$$\sum_{h} q_t^{h,c} \leq \text{ca}_c\cdot y_{c,t} \qquad \forall\, c,\ t, \tag{35}$$

$$\sum_{c} q_t^{c,p} \leq \text{ca}_p\cdot y_{p,t} \qquad \forall\, p,\ t, \tag{36}$$

$$\sum_{c} q_t^{c,br} \leq \text{ca}_{br}\cdot y_{br,t} \qquad \forall\, br,\ t, \tag{37}$$

$$\sum_{p} q_t^{p,u} \leq \text{ca}_u\cdot y_{u,t} \qquad \forall\, u,\ t, \tag{38}$$

$$\sum_{br} q_t^{br,dc} + \sum_{u} q_t^{u,dc} + \sum_{s} q_t^{s,dc} \leq \text{ca}_{dc}\cdot y_{dc,t} \qquad \forall\, dc,\ t. \tag{39}$$

Logical constraint: In this model, we have two types of binary variables: construction variables and availability variables. If a facility is built in one course, it can be used (available) from later courses. So if y $(t-1)$ is one, it means it is available from the previous period and no longer needs to be constructed in this period $(x(t)=0)$. In fact, it must have been built once from the first period to before the t period, and there is no need to rebuild it as shown in equations (40)–(46),

$$y_{uu,t} = y_{uu,t-1} + x_{uu,t} \qquad \forall\, uu,\ t>1, \tag{40}$$

$$y_{h,t} = y_{h,t-1} + x_{h,t} \qquad \forall\, h,\ t>1, \tag{41}$$

$$y_{c,t} = y_{c,t-1} + x_{c,t} \qquad \forall\, c,\ t>1, \tag{42}$$

$$y_{p,t} = y_{p,t-1} + x_{p,t} \qquad \forall\, p,\ t>1, \tag{43}$$

$$y_{u,t} = y_{u,t-1} + x_{u,t} \qquad \forall\, u,\ t>1, \tag{44}$$

$$y_{br,t} = y_{br,t-1} + x_{br,t} \qquad \forall\, br,\ t>1, \tag{45}$$

$$y_{dc,t} = y_{dc,t-1} + x_{dc,t} \qquad \forall\, dc,\ t>1. \tag{46}$$

Also, for the first period, availability means construction. This is shown in equations (47)–(53),

$$y_{uu,t} = x_{uu,t} \qquad \forall\, uu, t=1, \tag{47}$$

$$y_{h,t} = x_{h,t} \qquad \forall\, h, t=1, \tag{48}$$

$$y_{c,t} = x_{c,t} \qquad \forall\, c, t=1, \tag{49}$$

$$y_{p,t} = x_{p,t} \qquad \forall\, p, t=1, \tag{50}$$

Table 2. Payoff results of the two objectives.

	Total profit (milliard dollars/20 years)	Environmental impacts (million tons/20 years)
Maximize total profit	7439.34	1422.95
Minimize environmental impacts	7398.37	1129.64

$$y_{br,t} = x_{br,t} \qquad \forall\, br, t = 1, \tag{51}$$

$$y_{u,t} = x_{u,t} \qquad \forall\, u, t = 1, \tag{52}$$

$$y_{dc,t} = x_{dc,t} \qquad \forall\, dc, t = 1. \tag{53}$$

The increase in refinery's capacity production units cannot exceed a certain level. It is also possible to increase the capacity from the second period. The increases, as mentioned earlier, can be seen in equations (54) and (55),

$$l_t^{pu} = 0 \qquad \forall\, pu,\ t = 1, \tag{54}$$

$$\sum_t l_t^{pu} \le \text{capeak} \qquad \forall\, pu. \tag{55}$$

Inventory constraint: The inventory in each period is equal to the sum of the inventory of the previous period, and is also equal to the difference between the outputs and inputs to each storage centre in the same period, all of which are shown in equations (56)–(58),

$$\text{inv}_{t+1}^{so} = \text{inv}_t^{so} + \text{plus}_{t+1}^{so} \qquad \forall\, so, t, \tag{56}$$

$$\text{inv}_{t+1}^{s} = \text{inv}_t^{s} + \text{plus}_{t+1}^{s} \qquad \forall\, s, t, \tag{57}$$

$$\text{inv}_{t+1}^{c} = \text{inv}_t^{c} + \text{plus}_{t+1}^{c} \qquad \forall\, c, t. \tag{58}$$

The inventory of each storage centre's first period is equal to the difference between the outputs and inputs of the first period in the same storage centre,

$$\text{inv}_t^{so} = \text{plus}_t^{so} \qquad \forall\, so,\ t = 1, \tag{59}$$

$$\text{inv}_t^{s} = \text{plus}_t^{s} \qquad \forall\, s,\ t = 1, \tag{60}$$

$$\text{inv}_t^{c} = \text{plus}_t^{c} \qquad \forall\, c,\ t = 1. \tag{61}$$

5 Solution approach

Several methods have been proposed to solve multi-objective problems. These methods are classified into three categories: *priori*, interactive, and *posteriori*, depending on the type of decision-maker's role in decision-making. In *priori* methods, the decision maker is involved before the problem is solved. In interactive methods, communication with the decision maker is continuous and according to the received feedback, the calculations continue to converge to the desired result. In *posteriori* methods such as the ε-constraint method, a set of optimal Pareto points is first obtained, which the decision makers can choose according to their own priorities. In this paper, the ε-constraint method is used to solve the two-objective model. First, each of the goals is optimized separately, the results of which can be seen in Table 2. Then, one goal is considered as a constraint and the other is optimized to get the Pareto border according to Figure 2.

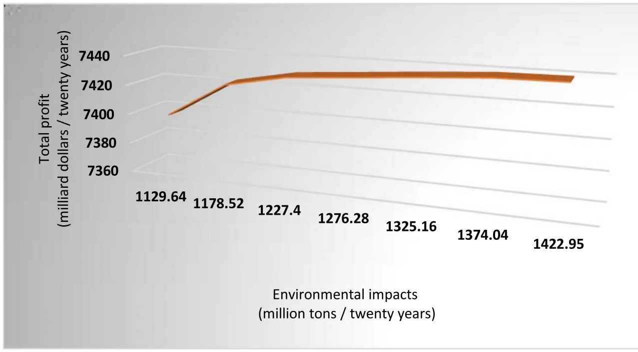

Fig. 2. Line representation of the Pareto optimal solutions.

6 Case study

In order to show the performance of the proposed model, the gas-oil and biodiesel supply network in Iran has been studied. The network includes 44 oil fields, 16 crude oil storage centers, 11 export terminals, 9 distillation units, 9 refinery production units, 9 potential locations for upgrading gas-oil supply chain units, 9 gas-oil and biodiesel storage centers, 10 potential locations for harvesting Jatropha, 10 potential locations for collecting Jatropha, 10 potential locations for pre-processing sites, 6 potential locations for upgrading units in the biodiesel supply chain, 6 potential locations for bio-refinery sites, 37 potential locations for distribution centers, 31 local customer centers, and finally 43 locations for Industry centers. The time horizon is 20 years. The provided information is summarized in the Table 3 (for more information please see Tables A.2, A.3 and A.4 from the Appendix).

Figure 3 shows the points in the network of case study. As can be seen in the figure, in the center of Iran the density of points is low. Conversely, in the southwestern border cities, the density is very high. The highest density rates

Table 3. Characteristics of case study supply chain elements.

Network element	Current	Potential	Number on the network
Oil field	✓		44
Crude oil storage center	✓		16
Export terminal	✓		11
Distillation unit	✓		9
Refinery production unit	✓		9
Upgrading unit in gas-oil supply chain		✓	9
Gas-oil and biodiesel storage center	✓		9
Jatropha harvesting center		✓	10
Jatropha collection center		✓	10
Pre-processing unit		✓	10
Upgrading unit in biodiesel supply chain		✓	6
Bio-refinery		✓	6
Distribution center		✓	37
Local customer	✓		31
Industry	✓		43

Fig. 3. Potential and current points in the network of case study.

Fig. 4. Current points in the network of case study.

of oil fields and other network elements exist in Khuzestan and Bushehr provinces.

Figure 3 shows all potential and actual points. After the equations in the model are solved and the answers are obtained, the set of network points will be as Figure 4. Crude oil is transported from 44 oil fields to crude oil storage centers. Crude oil is transferred directly to 11 export terminals or enters the country's refinery network through 16 crude oil storage centers to produce its derivatives. After being transferred to 9 refineries, the crude oil first enters the distillation tower and then enters the refinery's production units. The produced gas-oil is transferred to 9 product storage centers. All of these elements are typically present in the diesel supply chain and are actual. Data related to the elements have been extracted from the hydrocarbon balance sheet of Iran [58]. In the biodiesel supply chain, the 10 potential Jatropha planting centers transfer Jatropha to its collection centers. These collection centers have been selected from 10 potential centers. Jatropha is either moved directly from collection centers to bio-refineries or transferred to pre-processing units. Bio-refineries are selected from 6 potential centers and pre-processing units from 10 potential centers. After pre-processing, the bio-slurry enters the crude oil storage and bio-oils directly enter the upgrading units at oil refineries. These upgrading units are selected from 9 potential units. The materials coming out of the pre-processing units can be turned into the final product in the upgrading units that are in the biodiesel supply chain. Upgrading units in the biodiesel supply chain have been selected from 6 potential units. Data on potential locations of biodiesel supply chain elements are given in papers [11] and [59]. Biodiesel produced in bio-refineries and upgrading units in the biodiesel supply chain can be transported directly to distribution centers or first to product storage centers and then to distribution centers. Distribution centers are selected from 37 potential centers. Finally, fuel is transported from distribution centers to local customers in 31 provinces and industries that are the 43 major diesel power plants.

6.1 Results and discussion

The proposed model is coded in GAMS 24.1 optimization software and solved by CPLEX solver. The model characteristics are illustrated in Table 4.

In the Table 5, three models of gas-oil supply chain, non-integrated gas-oil and biodiesel supply chain, and integrated gas-oil and biodiesel supply chain (study done in this article) have compared. As can be seen, although the costs of the biodiesel supply chain increase compared to the

Table 4. Model statistics.

Model	Number of constraints	Number of continuous variables	Number of binary variables	Number of parameters
Multi-objective	10 709	119 244	3520	16 682

Table 5. Comparison between economic and environmental objective function in three models of gas-oil supply chain, non-integrated gas-oil and biodiesel supply chain, and integrated gas-oil and biodiesel supply chain.

Objective function	Total profit (milliard dollars/ 20 years)			Environmental impacts (million tons/20 years)		
	Gas-oil supply chain	Non-integrated gas-oil and biodiesel supply chain	Integrated gas-oil and biodiesel supply chain	Gas-oil supply chain	Non-integrated gas-oil and biodiesel supply chain	Integrated gas-oil and biodiesel supply chain
Maximization of total profit	7805.25	6895.19	7439.34	1691.15	1564.19	1422.95
Minimization of environmental impacts	7416.21	6651.59	7398.37	1471.29	1304.15	1129.64

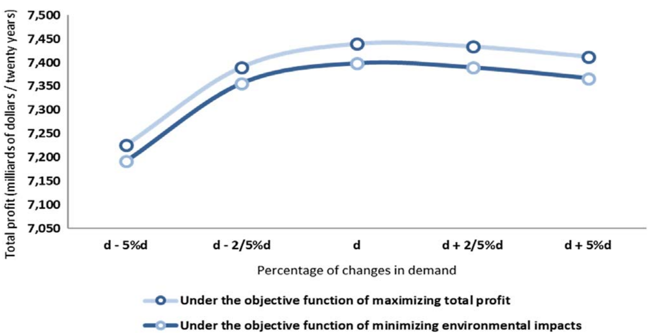

Fig. 5. Changes in total profits with changes in demand.

gas-oil supply chain due to the construction of some facilities, the amount of the environmental objective function improves. Also, as mentioned in this article, if we use the supply chain integration approach, we have economic savings compared to the non-integrated state.

Given that the model has been formulated and solved for a 20-year time horizon, it is necessary to analyze the effects of changes in demand over the years. In this regard, we analyze the effect of demand changes up to 5% more or less on model elements. Given that the importance of economic and environmental goals in different years varies according to the policies adopted, the analysis is performed for both objective functions.

Figure 5 shows the changes in total profit relative to the change in demand. In both objective functions, as the demand increases or decreases, the amount of total profit decreases. To analyze this issue, it is necessary to identify the elements that make up the total profit and have them studied. In general, it can be said that with the increase in demand, although revenues increase, the rate of increase in expenditures to meet the specific demand is higher than the increase in revenues. Moreover, the decrease in demand, as the costs also decrease, the rate of decrease in revenues is higher than the rate of decrease in costs.

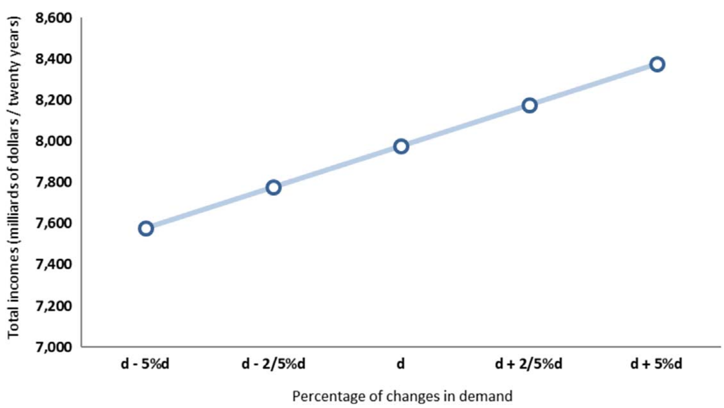

Fig. 6. Total income changes with changes in demand.

Table 6. Total costs changes with changes in demand.

Percentage of demand changes	Total cost under the objective function of minimizing environmental impacts (milliards of dollars/20 years)	Total cost under the objective function of maximizing total profit (million tons/20 years)	Percentage of difference between two economic and environmental objective functions
−5%	1009.37	964.03	5%
−2.5%	787.35	743.44	6%
0%	578.95	537.98	8%
+2.5%	421.84	387.77	9%
+5%	386.76	352.29	10%

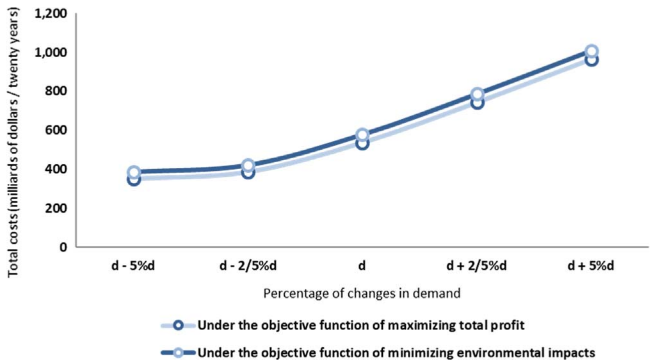

Fig. 7. Total costs changes with changes in demand.

Total income is generated through sales as much as demand, so the amount of income is equal for each economic and environmental goal. Figure 6 shows the rate of change in total income per change in demand. With increasing demand, total income will also increase.

The total cost increases with increasing demand. As shown in Table 6, costs vary between 5% and 10% when they depend on an economic or environmental objective. These percentages vary by several hundred milliards dollars. As shown in Figure 7, the graph's slope is less in the former parts of the graph. Given that the cost ratio is inversely related to total profit, Figure 5 shows that the first part of the diagram is sloping more.

The total amount of costs is derived from the sum of investment, transportation, operating, and holding costs. Due to the fact that the value of t is one year, in response to the model, the inventory has not been kept for 1 year. Therefore, investment, transportation, and operating costs must be investigated.

As shown in Figure 8, when the objective function is to maximize profits, investment costs, operating costs and transportation costs all increase with increasing demand. Also, in higher demand rates, the slope of changes in these costs increases with the change in demand. As can be seen in Figure 9, investment costs in both economic

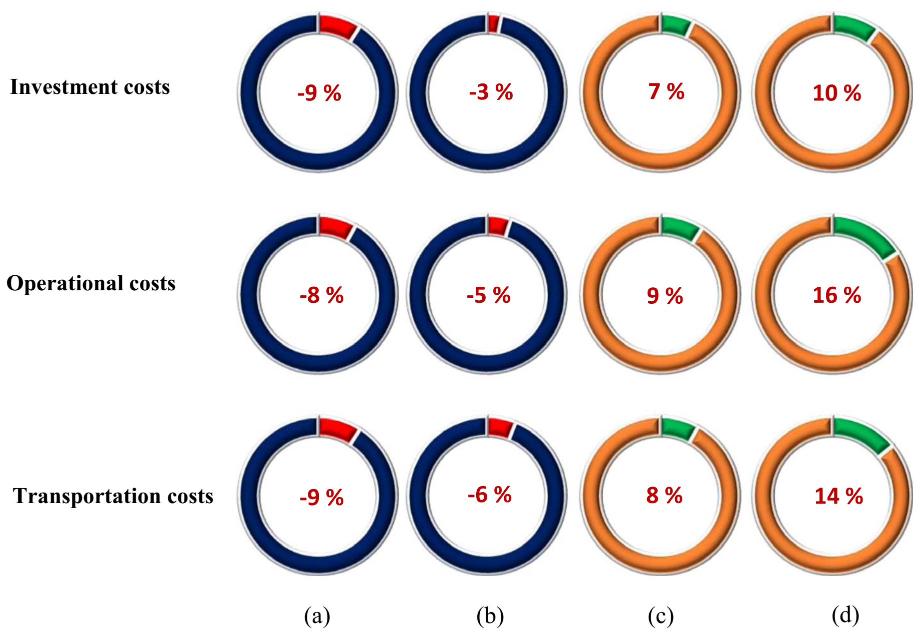

Fig. 8. Percentage of changes in investment costs, operating costs and transportation costs due to changes in demand, considering the profit maximization function as an objective function. (a) 5% reduction, (b) 2.5% reduction, (c) 2.5% increase, (d) 5% increase.

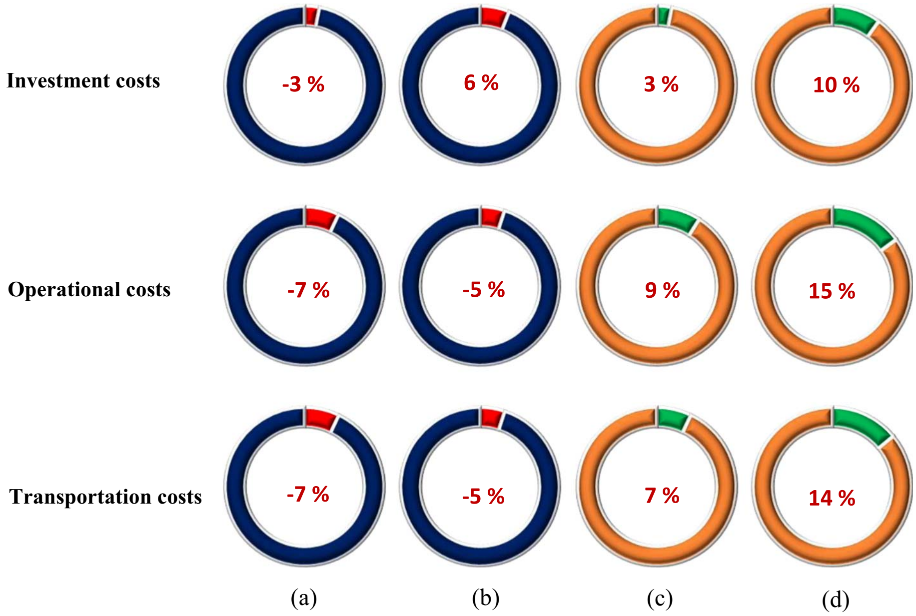

Fig. 9. Percentage of changes in investment costs, operating costs and transportation costs due to changes in demand, considering the environmental pollution minimization function as an objective function. (a) 5% decrease, (b) 2.5% decrease, (c) 2.5% increase, (d) 5% increase.

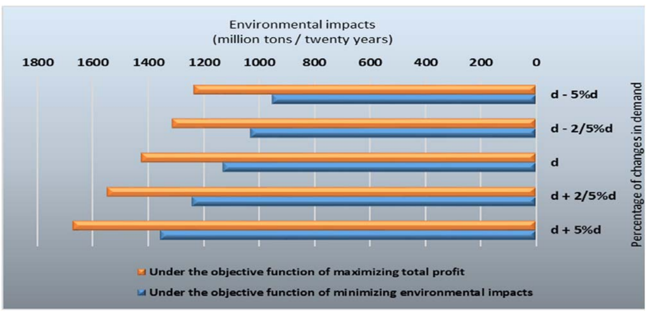

Fig. 10. Changes in environmental impacts with changes in demand.

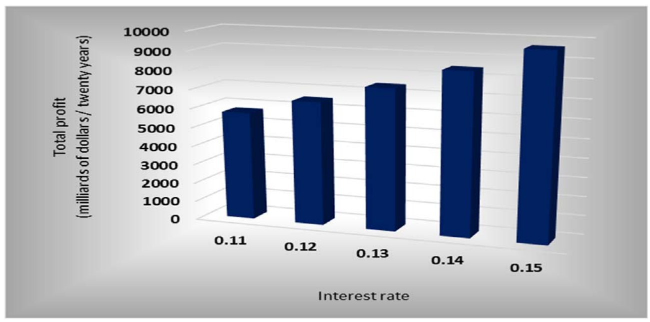

Fig. 11. Total profit changes with changes in interest rates.

Fig. 12. Total profit changes with changes in selling prices.

Fig. 13. Percentage of income from different sales routes.

and environmental functions do not change in the same way. In the environmental objective function, because the cost is not considered important, the amount of investment costs does not coincide with demand change. With the change in demand in order to minimize the environmental impact, construction sites will also change and may decrease or increase the investment costs. In the case of operating costs and transportation costs, they increase as demand increases.

Changing environmental impacts by changing demand is another critical issue, which is shown in Figure 10 for both economic and environmental objectives. As expected, as the demand increases, the amount of environmental impact increases, which is less when the objective is to minimize the environmental impact.

Interest rate changes are one of the essential factors in the profitability of the entire supply chain in its time horizon. Figure 11 shows the total profit changes per change in interest rates. In two ways, the chart is upward; Firstly, income is higher than cost, therefore with the increase in interest rates, the difference in current value of income and cost will increase. Secondly, a large part of the investment costs are incurred in the first period and therefore are not affected by the interest rate changes.

Changes in total profit relative to price changes can be seen in Figure 12. As it is known, due to the higher price and high volume of exports, the most significant impact is due to the increase in export prices. The least impact is on changes in selling prices to industries because industries seem to have less demand. Figure 13 shows the amount of income generated by selling the product in different ways. In Figure 12, price changes for exports have a much more significant impact on overall profits. Figure 13 also shows that most of the income comes from exports and a very tiny percentage from the industry.

7 Conclusion and future research direction

In recent years, finding alternative energy sources to fossil fuels has become an important issue in the world. In addition to reducing environmental pollution and being renewable, these resources must be economical. Biofuels are considered to be a good source of energy due to their credible properties.

This paper examines the composition of the oil-gas supply chain and the biodiesel supply chain and provides a model for using the oil gas network infrastructure to produce biodiesel to make biofuel production more economical. In this paper, for the first time, all the two supply chains' elements are considered and optimized with integration. All location decisions, selection of the connection point of two supply chains, allocation, production planning, inventory management, and capacity expansion are all done by solving the MILP model. In order to consider environmental aspects, the function of the second objective is also used. In addition to considering the amount of carbon dioxide emissions due to transportation in the network, the environmental objective function also considers the reduction of carbon dioxide emissions due to the use of biodiesel instead of gas-oil. In order to better evaluate the model, a real-world case study was performed in Iran and according to the data gathered, the model was solved and sensitivity analysis was performed. The multi-objective model was solved using the ε-constraint method and the Pareto boundary was obtained.

The model results show that with increasing demand, total profit does not necessarily increase because as demand increases, increasing costs is more considerable than increasing incomes. As demand declines, incomes decline more than costs do, and total profit declines as well. Therefore, at a certain point in demand, the total profit is the highest. Also, in order to make the whole supply chain more profitable, the effect of increasing export prices is more than increasing sales prices to local customers or industries. By reducing the production costs of biodiesel, the proposed model on the one hand, makes it more economical to use instead of gas-oil, and one the other hand, it is very effective in reducing the environmental pollution.

The above model can be expanded by considering social issues in order to achieve sustainable development. Also, considering uncertainty in important parameters such as demand, selling price and so forth can help make better decisions. Future researchers can consider second-generation biomass such as livestock waste and municipal wastewater that have the reliable potentiality in energy production.

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Appendix

Table A.1. The indices, parameters, and variables of the proposed model.

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
Parameters	
cc_t^{uu}	Cost of construction upgrading unit uu in gas-oil supply chain in period t ($/period)
cc_t^{pu}	Cost of expanding a unit capacity of refinery production unit pu in the gas-oil supply chain in the period t ($/period)
cc_t^{h}	Cost of purchasing a unit of the capacity of the Jatropha harvesting center h in period t ($/period)
cc_t^{c}	Cost of constructing the Jatropha collection center c in period t ($/period)
cc_t^{p}	Cost of constructing pre-processing unit p in period t ($/period)
cc_t^{dc}	Cost of construction distribution center dc in period t ($/period)
cc_t^{u}	Cost of constructing upgrading unit u in biodiesel supply chain in period t ($/period)
cc_t^{br}	Cost of construction bio-refinery br in period t ($/period)
dpr_t^{cu}	Demand of customer cu of fuel in period t (barrel/period).
dpr_t^{in}	Demand of industry in of fuel in period t (barrel/period).
dpr_t^{ex}	Demand of export terminal ex of fuel in period t (barrel/period).
dpr_t^{ex}	Demand of export terminal ex of crude oil in period t (barrel/period).
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 biodiesel 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 ($/period).
prcu_t	Selling price of fuel to customers in the period t ($/period)

(Continued on next page)

Table A.1. (Continued)

prex_t	Selling price of fuel to export terminals in the period t (\$/period)
prin_t	Selling price of fuel to industries in the period t (\$/period)
$d_{of,so}$	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)
$d_{h,c}$	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)
$d_{p,so}$	Distance between the pre-processing unit *p* and the crude oil storage *so* (km)
$d_{c,br}$	Distance between the collection center *c* and the bio-refinery *br* (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)
$d_{dc,cu}$	Distance between the distribution center *dc* and the customer *cu* (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 in period t (\$/period)
cprdu_t	Processing cost of distillation units in period t (\$/period)
cpruu_t	Processing cost of upgrading units in the gas-oil supply chain in period t (\$/period)
cprru_t	Processing cost of upgrading units in the biodiesel supply chain in period t (\$/period)
cprbr_t	Processing cost of bio-refineries in period t (\$/period)
cprp_t	Processing cost of pre-processing units in period t (\$/period)
ho_t^{so}	Cost of holding an inventory unit at the crude oil storage *so* in period t (\$/period)
ho_t^{s}	Cost of holding an inventory unit at the fuel storage center *s* in period t (\$/period)
ho_t^{c}	Cost of holding an inventory unit at the collection center *c* in period t (\$/period)
$\text{ctr}_{of,so}$	Cost of transporting between the oil field *of* and the crude oil storage *so* (\$)
$\text{ctr}_{so,ex}$	Cost of transporting between the crude oil storage *so* and the export terminal *ex* (\$)
$\text{ctr}_{so,du}$	Cost of transporting between the crude oil storage *so* and the distillation unit *du* (\$)
$\text{ctr}_{du,pu}$	Cost of transporting between the distillation unit *du* and the refinery production unit *pu* (\$)
$\text{ctr}_{pu,s}$	Cost of transporting between the refinery production unit *pu* and the fuel storage center *s* (\$)
$\text{ctr}_{uu,s}$	Cost of transporting between the upgrading unit *uu* in the gas-oil supply chain and the fuel storage center *s* (\$)
$\text{ctr}_{dc,ex}$	Cost of transporting between the distribution center *dc* and the export terminal *ex* (\$)
$\text{ctr}_{dc,cu}$	Cost of transporting between the distribution center *dc* and the customer *cu* (\$)
$\text{ctr}_{dc,in}$	Cost of transporting between the distribution center *dc* and the industry *in* (\$)
$\text{ctr}_{h,c}$	Cost of transporting between the harvesting center *h* and the collection center *c* (\$)
$\text{ctr}_{c,p}$	Cost of transporting between the collection center *c* and the pre-processing unit *p* (\$)
$\text{ctr}_{c,br}$	Cost of transporting between the collection center *c* and the bio-refinery *br* (\$)
$\text{ctr}_{p,u}$	Cost of transporting between the pre-processing unit *p* and the upgrading unit *u* in the biodiesel supply chain (\$)
$\text{ctr}_{p,uu}$	Cost of transporting between the pre-processing unit *p* and the upgrading unit *uu* in the gas-oil supply chain (\$)
$\text{ctr}_{p,so}$	Cost of transporting between the pre-processing unit *p* and the crude oil storage *so* (\$)
$\text{ctr}_{br,s}$	Cost of transporting between the bio-refinery *br* and the fuel storage center *s* (\$)
$\text{ctr}_{br,dc}$	Cost of transporting between the bio-refinery *br* and the distribution center *dc* (\$)

(Continued on next page)

Table A.1. (Continued)

$\text{ctr}_{s,dc}$	Cost of transporting between the fuel storage center s and the distribution center dc ($)
$\text{ctr}_{u,s}$	Cost of transporting between the upgrading unit u in the biodiesel supply chain and the fuel storage center s ($)
$\text{ctr}_{u,dc}$	Cost of transporting between the upgrading unit u in the biodiesel supply chain and the distribution center dc ($)
dr	Interest rate
chan	Conversion factor of millions of barrels to the number of fuel tankers
entr	Amount of carbon dioxide emissions per unit distance due to transportation in the supply chain (ton)
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
ca-peak	Maximum allowable increase in refinery capacity (barrel)
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 biodiesel supply chain in period t; 0 otherwise
y_t^{br}	1 if location br is active as the bio-refinery in period t; 0 otherwise
y_t^{dc}	1 if location dc is active as the distribution center in period t; 0 otherwise
Continous variables	
$q_t^{of,so}$	Quantity of crude oil transferred from the oil field of to the crude oil storage so in period t (barrel/period)
$q_t^{so,ex}$	Quantity of crude oil transferred from the crude oil storage so to the export terminal ex in period t (barrel/period)
$q_t^{so,du}$	Quantity of crude oil transferred from the crude oil storage so to the distillation unit du in period t (barrel/period)
$q_t^{du,pu}$	Quantity of intermediate product transferred from the distillation unit du to the refinery production unit pu in period t (barrel/period)
$q_t^{pu,s}$	Quantity of gas-oil transferred from the production unit pu to the fuel storage center s in period t (barrel/period)
$q_t^{uu,s}$	Quantity of biodiesel transferred from the upgrading unit uu in the gas-oil supply chain to the fuel storage center s in period t (barrel/period)
$q_t^{s,dc}$	Quantity of fuel transferred from the fuel storage center s to the distribution center dc in period t (barrel/period)
$q_t^{dc,ex}$	Quantity of fuel transferred from the distribution center dc to the export terminal ex in period t (barrel/period)

(Continued on next page)

Table A.1. (Continued)

$q_t^{dc,\mathrm{cu}}$	Quantity of fuel transferred from the distribution center dc to the customer cu in period t (barrel/period)
$q_t^{dc,in}$	Quantity of fuel transferred from the distribution center dc to the industry in in period t (barrel/period)
$q_t^{h,c}$	Quantity of Jatropha transferred from the harvesting center h to the collection center c in period t (ton/period)
$q_t^{c,p}$	Quantity of Jatropha transferred from the collection center c to the pre-processing unit p in period t (ton/period)
$q_t^{c,br}$	Quantity of Jatropha transferred from the collection center c to the bio-refinery br in period t (ton/period)
$q_t^{p,u}$	Quantity of intermediate product transferred from the pre-processing unit p to the upgrading unit u in the biodiesel supply chain in period t (barrel/period)
$q_t^{p,so}$	Quantity of bio-slurry transferred from the pre-processing unit p to the crude oil storage so in period t (barrel/period)
$q_t^{p,uu}$	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 (barrel/period)
$q_t^{br,s}$	Quantity of biodiesel transferred from the bio-refinery br to the fuel storage s in period t (barrel/period)
$q_t^{u,dc}$	Quantity of biodiesel transferred from the upgrading unit u in the biodiesel supply chain to the distribution center dc in period t (barrel/period)
$q_t^{br,dc}$	Quantity of biodiesel transferred from the bio-refinery br to the distribution center dc in period t (barrel/period)
$q_t^{u,s}$	Quantity of biodiesel transferred from the upgrading unit u in the biodiesel supply chain to the fuel storage s in period t (barrel/period)
l_t^{pu}	Amount of increase in the capacity of the refinery production unit pu in period t (barrel/period)
ca_t^{pu}	Capacity of refinery production unit pu in period t (barrel/period)
plus_t^{so}	The difference between inputs and outputs to the crude oil storage so in period t (barrel/period)
plus_t^{s}	The difference between inputs and outputs to the fuel storage s in period t (barrel/period)
plus_t^{c}	The difference between inputs and outputs to the collection center c in period t (barrel/period)
inv_t^{so}	Inventory of crude oil storage so in period t (barrel/period)
inv_t^{s}	Inventory of fuel storage s in period t (barrel/period)
inv_t^{c}	Inventory of collection center c in period t (barrel/period)
ctr_t	Transportation costs in the period t ($/period)
cop_t	Operational costs in the period t ($/period)
cinv_t	Investment costs in the period t ($/period)
ch_t	Holding costs in the period t ($/period)
inc_t	Income in the period t ($/period)
profit	Amount of economic objective function. The present value of the supply chain profit on the planning horizon ($)
income	The present value of supply chain revenue on the planning horizon ($)
cost	The present value of supply chain costs on the planning horizon ($)
envi_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 (ton/period)
envt_t	Amount of carbon dioxide emissions due to total supply chain transportation in the period t (ton/period)
enviro	Amount of environmental objective function (ton)

Table A.2. Capacity of distribution centers considered in this paper.

Capacity (m^3)	Distribution center	Capacity (m^3)	Distribution center	Capacity (m^3)	Distribution center
215188	Chabahar	21080	southern Khorasan	334900	Abadan
28816	Kohgiloyeh and Boyerahmad	516092	Khorasan Razavi	111660	Arak
52284	Chaharmahal va Bakhtiari	46110	North Khorasan	207116	Ardebil
740976	Kerman	152306	Zahedan	166783	Orumieh
183315	Yazd	114425	Zanjan	1598162	Esfahan
196670	Kermanshah	369780	Sari	143759	Karaj
219730	Golestan	118380	Shahroud	644853	Ahwaz
688838	Chalous	266090	Fars	129940	Ilam
208835	Gilan	97090	Sabzevar	317219	Bushehr
227456	Lorestan	126570	Ghazvin	697895	Tabriz
64246	Miandoab	202765	Qom	230287	Torbat heydarieh
1586840	Hormozgan	105253	Kurdistan	1255250	Tehran
				427099	Hamedan

Table A.3. Cost of construction of distribution centers.

Cost of construction (million dollar)	Distribution center	Cost of construction (million dollar)	Distribution center	Cost of construction (million dollar)	Distribution center
32.18	Chabahar	11.21	southern Khorasan	48.16	Abadan
9.17	Kohgiloyeh and Boyerahmad	73.6	Khorasan Razavi	16.65	Arak
10.97	Chaharmahal va Bakhtiari	15.69	North Khorasan	29.76	Ardebil
91.24	Kerman	32.96	Zahedan	24.15	Orumieh
33.29	Yazd	21.95	Zanjan	142.63	Esfahan
31.59	Kermanshah	52.96	Sari	20.64	Karaj
35.84	Golestan	19.9	Shahroud	88.11	Ahwaz
84.21	Chalous	41.11	Fars	18.64	Ilam
32.59	Gilan	24.25	Sabzevar	45.61	Bushehr
38.52	Lorestan	20.71	Ghazvin	96.3	Tabriz
12.96	Miandoab	33.8	Qom	33.12	Torbat heydarieh
104.58	Hormozgan	17.21	Kurdistan	145.63	Tehran
				60.08	Hamedan

Table A.4. Cost of purchasing a unit of the capacity of the Jatropha harvesting center.

Cost of purchasing (one thousand dollars per hectare)	Harvesting center	Cost of purchasing (one thousand dollars per hectare)	Harvesting center
284.96	Khuzestan	274.16	Ilam
275.44	Qom	284.02	Bushehr
273.04	Sistan and Baluchestan	278.92	Chaharmahal va Bakhtiari
275.44	Kermanshah	265.64	southern Khorasan
274.80	Hormozgan	271.76	Khorasan Razavi