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A multi-objective and multi-period model to design a strategic development program for biodiesel fuels

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ABSTRACT

The air pollution of conventional fuels, increases the tendency to alternative cleaner fuels like biodiesel fuels. Biodiesel is an expensive fuel and can be used as an additive to reduce levels of particulates, carbon monoxide, and other pollutants released from diesel fuel. The proportion of biodiesel in the produced fuel can be planned and controlled according to the conditions. This study forms a comprehensive multi-objective-period model for designing a biodiesel development program and compares different biodiesel blends and primary resources. The study considers B5, B10, B20, B40, and B100 along with diesel as the candidate fuels for demand fulfillment; furthermore, model considers waste cooking oil, soya, sunflower, and rapeseed as the primary resources. The objectives are the facilities' implementation costs and environmental effects minimization. The decision variables are the capacity planning and the facility location variables. The exact Pareto set is obtained by using the augmented e-constraint method. The study considers economic and environment objectives interactions. Based on the results, B5 and B40 are the most appropriate options in the exact Pareto set; moreover, the results show the advantages of this approach to select the most appropriate fuels and primary resources according to different conditions during the studied period.

Introduction and literature review

Due to the value of non-energy uses of fossil fuel products in industries (for example petrochemical industries that produce various and valuable products by reforming methane and propane) along with the high price of crude oil and global environmental problems, focusing on new energy resources have been increasing across the world. Moreover, the air pollution of fossil fuels, especially in urban areas, raises the tendency to alternative fuels such as biodiesel. Biodiesel can be used as a fuel in the pure form; however, due to its cost, it is usually used as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons derived from diesel-powered vehicles [1]. The use of biodiesel-diesel blends in CI engines has been proven to lead to a great decrease in particulate matter, hydrocarbon, and carbon monoxide compared to diesel fuel. There are different ideas about nitrogen oxides. Some researches show an increase [2], and some others show a decrease in the quantity of nitrogen oxide [3]. Many researches were conducted on the life cycle assessment (LCA) of biofuels to specify the environmental impacts of them and compare them with conventional fuels [4–7]. Altamirano et al. [8] tracked CO2 emissions, energy efficiency, water and resources consumption, and environmental impacts of two biodiesel production chains.

Biodiesel is produced using transesterification. Feedstocks for biodiesel include animal fats, vegetable oils, soy, rapeseed, jatropha, sunflower, palm oil, field pennycress, algae, waste cooking oil, etc. Thus, biofuel is a renewable fuel since its feedstocks are always available;

Furthermore, some of the feedstocks are municipal, industrial, or agriculture waste. Therefore, using these feedstocks for producing biofuel, in addition to reducing pollution, also helps to manage wastes. Cambero et al. [9] and Zhong et al. [10] considered some social and environmental advantages of bioenergy and biofuel supply chains.

In recent years, the biofuel industry has become complicated which make it increasingly difficult to be analyzed and optimized [11]. The high cost of such fuels restricts their application; an approach to dealing with this problem is studying and optimizing their supply chains. For this purpose, many studies were carried out that consider different aspects. Ghaderi et al. [12] reviewed 146 papers on the supply chains of

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the biomass-based energy systems. Furthermore, Atashbar et al. [13] present a classification of optimization methods and models developed for biomass supply chains.

An economic model was developed by Whalley et al. [14] to estimate the delivery cost of biomass chips to a biorefinery. Zhang et al. [15] developed a new multi-agent feedstock supply model specifically for China. Senna et al. [16] presented a comparison between a two-stage model and a multistage stochastic model to optimize the biodiesel supply chain. Golecha et al. [17] suggested a cost model for biomass transportation from a field to a conversion facility. Hao Hu et al. [18] have considered a cyber GIS approach to optimize biomass supply chains under uncertainties. A mathematical model was presented by Mirkouei et al. [19] for determining the optimal combination and location of refineries for a known quantity of woody biomass. An RDEA-based algorithm was proposed by Grigoroudis et al. [20] for the optimal design of supply chain networks. Ivanov et al. [21] addressed the optimal design and location facility of biodiesel supply chains under economic and environmental criteria. Azadeh et al. [22] analyzed the challenges of supplying biomass to biorefineries and shipping biofuel to demand centers. Yazan et al. [23] compared different second-generation biomass supply chain designs focusing on mobile pyrolysis plants and centralized versus a decentralized collection of biomass regarding economic and environmental sustainability. Osorio-Tejada et al. [24] compared biodiesel and liquefied natural gas as alternative fuels in transport systems. A stochastic bi-objective Mixed Integer Problem model was presented by Cáceres [25] to optimize biodiesel supply chain networks.

Some other studies considered similar subjects in other areas. For example, the grid design and optimal allocation of wind and biomass resources for renewable electricity supply chains are studied by Osmani et al. [26]. Tan et al. [27] focused on the fuel supply chain of biomass direct-fired power generation. Their objectives comprise profit and social welfare maximization. Xiaojing et al. [28] studied improving the efficiency of biogas feedback supply chain. Woo et al. [29] presented a new optimization-based approach for the design and operation of a renewable hydrogen system from various types of biomass. Moreover a similar study was carried out by Guillén et al. [30]. They addressed the design of hydrogen supply chains for vehicle use with economic and environmental concerns. Jeong et al. [31] developed a mixed-integer linear programming model associated with a geographic information system to optimize a supply chain for biodiesel produced from camelina oilseed.

Laporte et al. [32] assessed the supply of switchgrass and miscanthus in Canada, under different biomass prices and supply chain structures, using an integrated economic, biophysical and GIS model, to assess bioenergy policy. Lainez-Aguirre et al. [33] presented a flexible supply chain superstructure to deal with issues on economic and environmental benefits achievable by integrating biomass-coal plants, and CO_2 capture and utilization plants.

Table 1 shows a review of some other related works carried out in recent years. Most of these researches selected just one fuel such as B5 and studied its economic, environmental, or technical aspects. But it is important why the fuel is selected, and which fuel is the best according to the conditions. Since biodiesel can be used as an additive to conventional fuels and the share of it in the new fuel is effective on the released pollution, the volume of required biodiesel, and the cost of the new fuel, it is necessary to know which fuel and when should be produced. It might be possible and effective to use several biodiesel blends simultaneously in different periods instead of using only one fuel. This can lead to a decrease in costs and can help the government to accelerate the development of these kinds of fuels. These studies haven't discussed this statement and have failed to suggest development plans for these kinds of fuels. This study aims to propose a mathematical framework to investigate the best blends of biodiesel fuel. In the following, the contribution of the paper has been demonstrated in detail.

Considering the high cost of biodiesel, it seems that the blends of biodiesel and conventional hydrocarbon-based diesel could be more economical since the cost is an obstacle in the way of widespread use of these fuels. Therefore, these blends (B40, B20, B10, and B5) are the most common fuels in the retail diesel fuel market and have different price and released pollutant. Mentioned studies have focused on various aspects of biofuels supply chains. Primary resources, produced fuels, and objectives are different among the studies. As mentioned, most of the related researches investigate solely one fuel or consider only one resource as a feedstock which may not be optimum. On the other hand, it is difficult to choose the best biodiesel blends and resources among the candidates. Therefore, in this study, a comprehensive multi-objective and multi-period MIP model is proposed to compare these fuels and select one or more of them to fulfill fuel demand in the study period. This model also suggests the best primary resources for each year of the studied period.

The proposed biofuel supply chain includes different facilities such as oil extraction plants, waste oil refineries, biodiesel and fuel blending plants and different products such as biodiesel blends and glycerin as well. For this purpose, B5, B10, B20, B40, and B100 are considered as the candidate blends and waste cooking oil, soya, sunflower, and rapeseed as the primary resources. Based on the results of this model, the capacity of facilities will be determined in the model's horizon. Furthermore, the type of fuels that the decision-makers should concentrate on will be chosen. This information can be used for designing a development plan for biodiesel fuels in countries and big cities.

The rest of this paper consists of two main sections. In the first section, the model is described. This section discusses the proposed supply chain and then presents the mathematical model's objectives and constraints, respectively. The results obtained after running the model for a case study are presented in the second section. In this section, the results of the running and some sensitivity analyses for some parameters are brought in the form of several trends, tables, and figures.

Model

Proposed supply chain

Different kinds of crops are suitable as a primary resource for producing biodiesel. The proposed model considers waste cooking oil and three crops, namely soya, sunflower, and rapeseed. The oil of crops is extracted in extraction plants, and the waste cooking oil is refined in waste oil refineries. Then, they are transported to biodiesel refineries and transformed into biodiesel and glycerin. Biodiesel and glycerin are produced according to the transesterification process as shown below [34].

$$Oil + Methanol \rightarrow Biodiesel + Glycerin \tag{1}$$

Next, produced glycerin is transported to glycerin distributor and then to glycerin demand centers. Additionally, the produced biodiesel is delivered to blending plants along with diesel fuel; in each candidate region, all biodiesel blends, namely B5, B10, B20, B40, and B100 can be produced. Afterward, these fuels are sent to demand centers. Furthermore, the proposed model considers the import of oil, biodiesel, and crops from outside of the study area. Fig. 1 shows the diagram of this process.

Some factors like cetane number, oxidation stability, iodine number are necessary for blending diesel and biodiesel from different sources. However, this study ignores them because of simplification.

Mathematical model

This section explains the mathematical model of the proposed supply chain. First, the objective functions, and then, the constraints are mentioned. Table 2 shows the nomenclature of the model.

Table 1
Literature review.

Ref	Year	Subject	Resource	Fuel	Model & Solving method
[42]	2018	Environmental and techno-economic considerations	Frying oil	Biodiesel	–
[43]	2018	Techno-economic analysis	Palm oil	Biodiesel	Techno-economic analysis Simulation
[44]	2018	design biodiesel supply chain	Jatropha, waste oil cooking and microalgae	biodiesel	MILP
[45]	2018	Scale-up and economic analysis	Recycled grease trap waste	Biodiesel	Economic feasibility Simulation
[11]	2017	To quantify and control the impact of biomass quality variability on supply chain related decisions and technology selection	Biomass	Biofuel	An L-shaped and a multicut L-shaped method
[46]	2017	To design a sustainable multi-period supply chain	2th generation biomass	Bioethanol	Augmented ε-constraint method
[47]	2017	The strategic design of biodiesel supply chain network	Jatropha, curcas, waste cooking oil	Biodiesel	DEA & MILP
[48]	2017	Supply chain network design	Jatropha seeds, waste cooking oil	Biodiesel	MILP
[49]	2017	Finding the optimal production and investment plan for a biogas supply chain	Straw, sugar beet and manure	Natural gas, heat, and electricity	MIP
[50]	2017	A novel biorefinery concept for lignocellulosic biomass	Black liquor, Sawdust, Straw	Biofuel	–
[51]	2017	The fuel supply chain of biomass direct-fired power generation	Biomass	Biomass	–
[52]	2016	An Overview on Production, Properties, Performance and Emission Analysis	–	B20, B100, E10, M10	Overview
[53]	2016	Proposing a sustainable supply chain model capable of revealing opportunities and limitations	Microalgae	Biofuel	biofuel
[54]	2016	Design and plan a supply chain from fields to consumption markets	Biomass	Biodiesel	System dynamics-MIP
[55]	2016	Locating biofuel facilities and designing a supply chain to minimize the overall cost	Woody biomass	Biofuel	MILP
[56]	2016	A two-stage model for the design and planning of a microalgae-based supply chain.	Microalgae	Biodiesel	Robust mixed-integer linear programming
[57]	2016	The optimal design of supply chains considering all policy instruments of European regulations.	Lignocellulosic biomass	Biofuel	–
[58]	2016	Maximizing the supply chain of a forest-based biomass power plant	Forest-based biomass	electricity	MILP-Robust optimization
[59]	2016	An optimization by considering all the dimension of the sustainable development	1th and 2th generation biomass	Bio-ethanol	MILP
[60]	2016	the design of an integrated biodiesel-petroleum diesel blends system	sunflower, rape and other oil seed crops	B100	MILP
[39]	2016	The performance and emission of diesel engine with soybean and waste oil biodiesel fuels	–	B5, B10, B15, B20 and B50	Experiment
[61]	2015	Studying of the optimal conditions of the supply chain biodiesel via the techno-economic and environmental analysis.	Oil palm crop	B20	MOMILP
[40]	2015	Effect of different percentages of biodiesel–diesel blends on a diesel engine	–	B5, B10, B15, B20, B25, B50 and B100	Experiment
[62]	2015	the best biodiesel blend selection	–	B20, B40, B60, B80, B100 and Diesel	MCDM
[63]	2015	Strategic planning design of a supply chain network	Microalgae	Biodiesel	MILP
[64]	2015	Supply chain design and planning for biomass to electricity	Residual forestry biomass	Bioelectricity	MILP
[65]	2015	Determine the optimal supply chain design and operation, under uncertainty.	Wastes or lignocellulosic feedstocks	Biofuel	MILP
[66]	2014	A life cycle assessment (LCA) based supply chain model	Biomass	Bio-ethanol, Bio-methanol, Bio-diesel	MOMILP
[67]	2014	Analyzing of The production chain of biofuels from agricultural residues	Agricultural residues	Biofuel	MILP
This study		To design a strategic development program	Waste cooking oil, Soya, Sunflower, and Rapeseed	B5, B10, B20, B40, B100	MOMILP

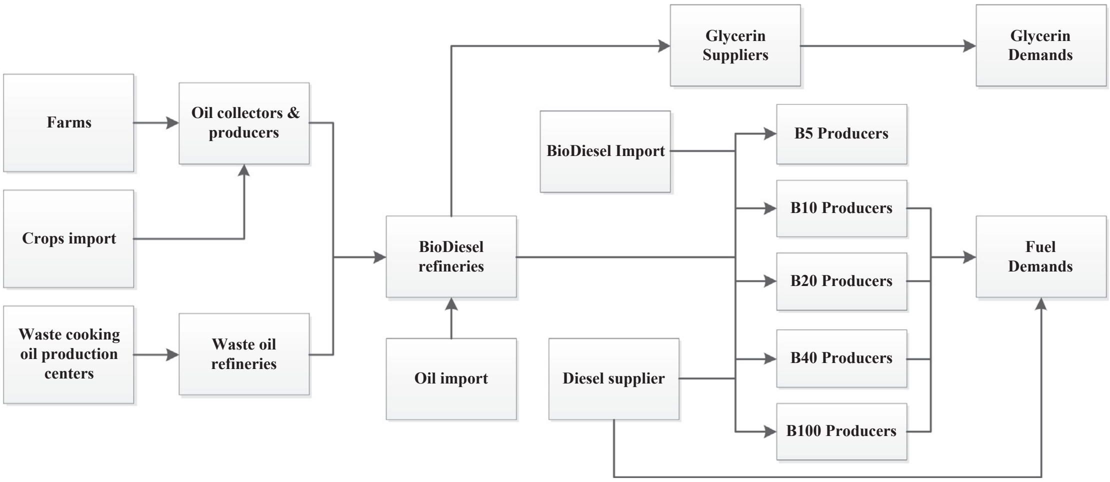

Fig. 1. Proposed flowchart for biodiesel supply chain.

Table 2
Nomenclature.

Indexes			
G	Farm	gli	Glycerin
T	Optimization period	GL	Glycerin distributor locations
P	Crops	GLD	Glycerin demand centers
O	Oil extraction plant locations	WP	Waste cooking oil producer centers
B	Biodiesel production plant locations	W	Waste cooking oil refinery locations
F	Fuel production plant locations	D	Diesel
K	Type of Biodiesel fuel	C	Fuel demand centers
Parameters			
I	Real interest rate (percent)	$D_{GLD,T}$	Demand for glycerin at time T
$\alpha_{P,G}$	Yielded crop P in farm G (Tonne per hectare)	M	A big number
$\alpha_{P,O}$	Efficiency of oil extraction plant O for crop P	s_K	Share of biodiesel in each fuel (5% for B5, …, 100% for B100)
α_W	Efficiency of waste cooking oil refinery (percent)	$Worth_{GLI}$	Price of Glycerin
α_B	Efficiency of biodiesel production plant (percent)	Em_B	Emission from biodiesel
α_{gli}	Efficiency of glycerin production plant (percent)	Em_D	Emission from diesel
$D_{C,T}$	Demand for fuel in demand center C at time T		
Decision variables			
Continues variables		$S_{W,B,T}$	Quantity of transmitted refined oil from plant W to plant B at time T
$H_{P,G,T}$	Harvested crop P from farm G at time T	$S_{O,B,T}$	Quantity of transmitted oil from plant O to plant B at time T
$A_{P,G,T}$	Area of used farm for harvesting crop P in place G	$S_{B,F,T}$	Quantity of transmitted biodiesel from plant B to plant F at time T
$FO_{P,O,T}$	Quantity of Crop P received by plant O at time T	$S_{F,K,C,T}$	Quantity of transmitted Fuel type K from plant F to demand center C at time T
$IP_{P,O,T}$	Imported crop P at time T for plant O	$S_{B,GL,T}$	Quantity of transmitted glycerin from plant B to distributor GL at time T
$PO_{O,T}$	Produced oil in plant O at time T	$S_{GL,GLD,T}$	Quantity of transmitted glycerin from distributor GL to demand center GLD at time T
$WO_{WP,T}$	Quantity of waste cooking oil collected from producer WP at time T	$CO_{O,T}$	Added capacity of oil extraction Plant O at Time T
$FWO_{W,T}$	Quantity of waste cooking oil received by plant W at time T	$CB_{B,T}$	Added capacity of biodiesel refinery B at Time T
$PRW_{W,T}$	Refined waste cooking oil in plant W at time T	$CB_{B,Gli,T}$	Added capacity of biodiesel refinery B for glycerin at Time T
$FB_{B,T}$	Quantity of oil received by plant B at time T	$CW_{W,T}$	Added capacity of waste cooking oil refinery Plant W at Time T
$IO_{B,T}$	Quantity of imported oil received by plant B at time T	$CF_{F,T}$	Added capacity of Fuel Plant F for fuel K at Time T
$PB_{B,T}$	Produced biodiesel in plant B at time T	$CGL_{GL,T}$	Added capacity of glycerin distributor at Time T
$FF_{F,T}$	Quantity of biodiesel received by plant F for fuel K at time T	Ob_1	First objective function (cost)
$IB_{F,T}$	Quantity of imported biodiesel received by plant F at time T	Ob_2	Second objective function (pollution)
$PF_{K,F,T}$	Produced fuel K in plant F at time T	Binary variables	
$GOS_{K,F,T}$	Consumed diesel for fuel K in plant F at time T	$YA_{P,G,T}$	When farm G is assigned for harvesting crop P at time T equals 1 and else equal 0
$SD_{F,T}$	Quantity of transmitted diesel to plant F at time T	$Y_{O,T}$	When plant O is constructed or expanded at time T equals 1 end else equal 0
$GD_{C,T}$	Consumed diesel for satisfying fuel demand	$Y_{W,T}$	When plant W is constructed or expanded at time T equals 1 end else equal 0
$PGL_{B,T}$	Produced glycerin in plant B at time T	$Y_{B,T}$	When plant B is constructed or expanded at time T equals 1 end else equal 0
$FGL_{GL,T}$	Quantity of glycerin received by distributor GL at time T	$Y_{F,T}$	When plant F for Fuel K is constructed or expanded at time T equals 1 end else equal 0
$IGL_{GLD,T}$	Quantity of imported glycerin received by demand center GLD at time T	$V_{K,F,T}$	When produced fuel K at time T greater than 0 this variable is equal 1 and otherwise is equal 0.
$S_{P,G,O,T}$	Quantity of transmitted crop P from farm G to plant O at time T	$Y_{GL,T}$	When distributor GL is constructed or expanded at time T equals 1 end else equal 0
$S_{WP,W,T}$	Quantity of transmitted waste cooking oil from producer WP to plant W at time T		

Table 3
The intended values for the indexes.

Index	Value	Remark
G	3 regions	Assumption
T	20 years	Assumption
P	3 crops	Assumption
O	3 regions	Assumption
B	3 regions	Assumption
F	3 regions	Assumption
GLD	2 regions	Assumption
W	3 regions	Assumption
GL	2 regions	Assumption
C	2 regions	Assumption
WP	3 regions	Assumption
K	B5, B10, B20, B40, B100	Assumption

Objective functions

For a comprehensive study of the biofuels supply chain, different objectives, e.g. cost, environmental effects, and social goals can be regarded. The minimization of costs and environmental effects are the objective functions in this study.

The cost objective function (Eq. (2)) includes the fixed and variable cost of facilities, primary resources, conversion, importing, transportation, diesel, and incomes.

$$\begin{aligned}&Min\ Ob_1 = Fixed\ \&\ variable\ costs\ of\ facilities\ (refining\ and\ collecting\ waste\\ &\quad oil\ and\ crops,\ bio\ refineries,\ blending\ plants,\\ &glycerin\ suppliers + land\ \cos t) + \cos t\ of\ cultivation + Transportation\\ &\quad \cos t + Diesel\ for\ demand + refining\ and\ producing\\ &\quad \cos t\ (crops,\ waste\ oil,\ oil,\ glycerin,\ biodiesel,\\ &fuel) + importing\ \cos t\ (oil,\ biodiesel,\ diesel,\ crops,\ glycerin) - glycerin\\ &\quad sell\ income\end{aligned} \tag{2}$$

The second objective (Eq. (3)) considers emission from fuels consumption.

$$Min\ Ob_2 = (GD_{C,T} \times Em_D) + \sum_T \sum_K \left(Em_K \times \sum_F \sum_C S_{F,K,C,T} \right) \tag{3}$$

The emission of each type of biodiesel fuel is calculated with the following equation (Eq. (4)):

$$Em_K = s_K \times Em_B + (1 - s_K) \times Em_D \tag{4}$$

where s_K is the share of biodiesel in the consumed fuel.

Constraints

This section presents the constraints of the model. These constraints are divided into three classes. The first class is about the conversion and balance of material in facilities. The second class is about the capacity planning and facility location and the third class shows material flows between facilities. The following equations explain these constraints.

$$H_{P,G,T} \le \sum_T A_{P,G,T} \times \alpha_{P,G} \quad \forall\ P,\ G,\ T \tag{5}$$

$$A_{P,G,T} \le M \times YA_{P,G,T} \quad \forall\ P,\ G,\ T \tag{6}$$

Eq. (5) shows the calculation of the volume of harvesting crops. This equation conveys that the harvested crops should be lower than the capacity of available farms. Moreover, Eq. (6) explains the relationship between $YA_{P,G,T}$ and the area of the farms. $YA_{P,G,T}$ and other binary variables in this study have been used in the cost objective function for the calculation of the fixed cost of facilities.

$$\sum_O S_{P,G,O,T} \le H_{P,G,T} \quad \forall\ P,\ G,\ T \tag{7}$$

Table 4
The intended values for the parameters.

Name	Unit	Value	Reference
I	Percent	5%	[68]
$\alpha_{P,G}$(for p)	Tonne/Hectare	(4, 45, 4.3, 3.98)	Expert
α_{gli}	Percent	$1 - \alpha_B$	[47]
α_B(crop)	Percent	83%	[47]
α_B(waste oil)	Percent	90%	[69]
α_W	Percent	95%	[47]
$\alpha_{P,O}$(for P)	Percent	(35%, 45%, 35%)	Expert
$VCt_{P,G,T}$	$/Tonne	15.44	[55]
Time dependent transportation cost	Truckload/Hour	32	[54]
Distance dependent transportation cost	Truckload/Mile	1.3	[54]
Truck capacity (Bulk solid)	Wet Tonne	25	[54]
Truck capacity (liquid)	gallon (25 Tonne oil)	8000	[54]
$VCt_{D,T}$	$/liter	0.25	Expert
Carbon residue (Biodiesel)	Percent	0.33%	[41]
Carbon residue (Commercial diesel fuel)	Percent	0.4%	[41]
Glycerin price	$/Kg	0.79	[41]
$VOCt_{O,P,T}$	$/Tonne	600	Expert
$VOCt_{W,T}$	$/Tonne	450	Expert
$VOCt_{B,T}$	$/Tonne	600	Expert
$VCt_{gli,T}$	$/Tonne	200	Expert
$VOCt_{F,K,T}$ (for K)	$/Tonne	(600, 600, 600, 600, 100)	Expert
$VOCt_{GL,T}$	$/Tonne	100	Expert
$VCt_{W,T}$	$/Tonne	50	Expert
$VCt_{IMP,P,T}$	$/Tonne	100	Expert
$VCt_{B,T}$	$/Tonne	60	Expert
$VCt_{gli,T}$	$/Tonne	30	Expert
$VCt_{O,P,T}$ (for P)	$/Tonne	(20, 22, 24)	Expert
$VCt_{WP,T}$	$/Tonne	100	Assumption
$VCt_{G,T}$	$/Hectare	1500	Assumption
$VCt_{F,K,T}$ (for K)	$/Tonne	(60, 60, 60, 60, 30)	Assumption
Fixed costs	$	10	Assumption

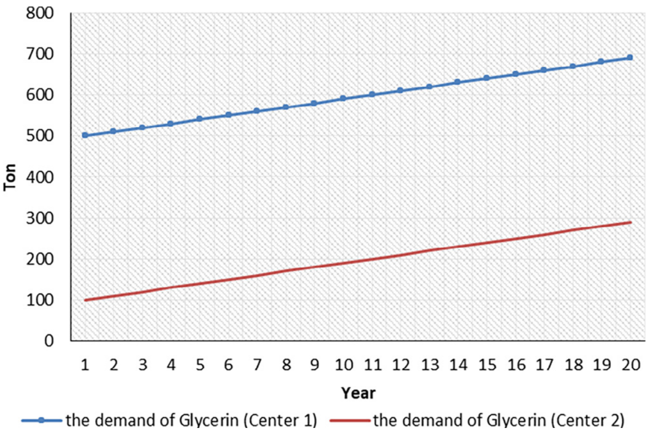

Fig. 2. The demand for glycerin.

$$\sum_P \sum_G S_{P,G,O,T} \le M \times \sum_{t=0}^{T-1} Y_{O,T} \quad \forall\ O,\ T \tag{8}$$

Eqs. (7) and (8) show relationships among the transported, harvested and imported crops. Eq. (7) states the flow of harvested crops from a region to different oil extraction plants. Furthermore, Eq. (8) shows the existence of the capacity of the oil extraction plant. This constraint conveys that crops are sent to a region if there is an oil

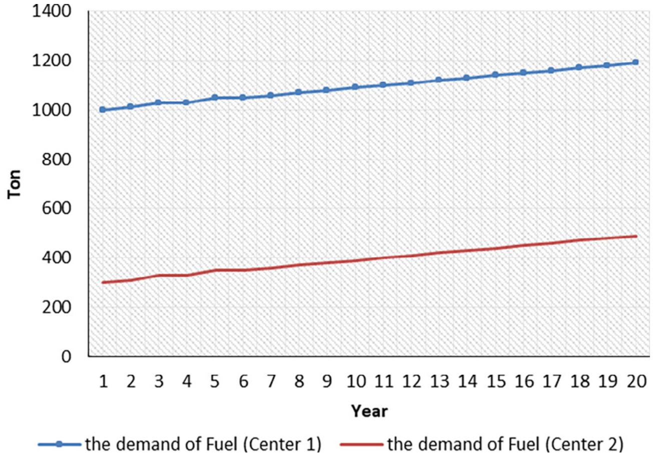

Fig. 3. The demand for fuel.

extraction plant available in that region.

$$FO_{P,O,T} \le IP_{P,O,T} + \sum_{G} S_{P,G,O,T} \quad \forall\ P,\ O,\ T \tag{9}$$

The volume of received crops in an oil extraction plant must be lower than the total transported crops from different farms to that plant and imported crops for that plant. Eq. (9) presents this relationship. Eq. (10) shows the relationship between received crops and produced oil in an oil extraction plant at time T.

$$PO_{O,T} \le \sum_{P} \alpha_{P,O} \times FO_{P,O,T} \quad \forall\ O,\ T \tag{10}$$

The sum of waste oil that is sent from a region to different waste oil refinery plants must be lower than collected waste oil in that region. Eq. (11) presents this concept. Eqs. (12) and (13) mention the relationship between the transported waste oil from different regions and received waste oil in a refinery plant.

$$WO_{WP,T} \ge \sum_{W} S_{WP,W,T} \quad \forall\ WP,\ T \tag{11}$$

$$FWO_{W,T} \le \sum_{WP} S_{WP,W,T} \quad \forall\ W,\ T \tag{12}$$

$$\sum_{WP} S_{WP,W,T} \le M \times \sum_{t=0}^{T-1} Y_{W,T} \quad \forall\ W,\ T \tag{13}$$

Eq. (14) shows the relationship between refined waste oil and waste cooking oil.

$$PRW_{W,T} \le \alpha_{W} \times FWO_{W,T} \quad \forall\ W,\ T \tag{14}$$

The restrictions of transported oil from waste oil refineries and oil extraction plants to biodiesel refineries are presented in Eqs. (15) and (16). Based on Eq. (15), refined cooking oil in a refinery should be higher than the sum of refined oil that is sent from that refinery to different biodiesel plants. The similar concept for extracted oil from crops is explained in Eq. (16).

$$PRW_{W,T} \ge \sum_{B} S_{W,B,T} \quad \forall\ W,\ T \tag{15}$$

$$PO_{O,T} \ge \sum_{B} S_{O,B,T} \quad \forall\ O,\ T \tag{16}$$

The received oil in biodiesel refineries is calculated by Eqs. (17) and (18). Eq. (17) conveys that received oil in a biodiesel production plant is lower than the sum of the imported oil, refined cooking oil, and extracted oil that is sent from different plants to that biodiesel plant. Furthermore, Eq. (18) shows that the imported oil, refined cooking oil, and extracted oil are sent to a biodiesel plant in place B if there is available capacity.

$$FB_{B,T} \le IO_{B,T} + \sum_{W} S_{W,B,T} + \sum_{O} S_{O,B,T} \quad \forall\ B,\ T \tag{17}$$

$$IO_{B,T} + \sum_{W} S_{W,B,T} + \sum_{O} S_{O,B,T} \le M \times \sum_{t=0}^{T-1} Y_{B,T} \quad \forall\ B,\ T \tag{18}$$

Eq. (19) presents the quantity of produced biodiesel.

$$PB_{B,T} \le \alpha_{B} \times FB_{B,T} \quad \forall\ B,\ T \tag{19}$$

Eqs. (20) and (21) show the flow of biodiesel from biodiesel plants to fuel blending plants. Eq. (20) states that produced biodiesel in a biodiesel plant should be higher than the sum of biodiesel that is sent to different fuel blending plants from that biodiesel plant. Moreover, the sum of imported biodiesel for a fuel blending plant and transported biodiesel from different biodiesel refineries to the fuel blending plants should be lower than the received biodiesel in that blending plant (Eq. (21)). Eq. (22) shows the relationship between the existence of a capacity for fuel blending in a region and receiving biodiesel in that region.

$$PB_{B,T} \ge \sum_{F} S_{B,F,T} \quad \forall\ B,\ T \tag{20}$$

$$FF_{F,T} \le IB_{F,T} + \sum_{B} S_{B,F,T} \quad \forall\ F,\ T \tag{21}$$

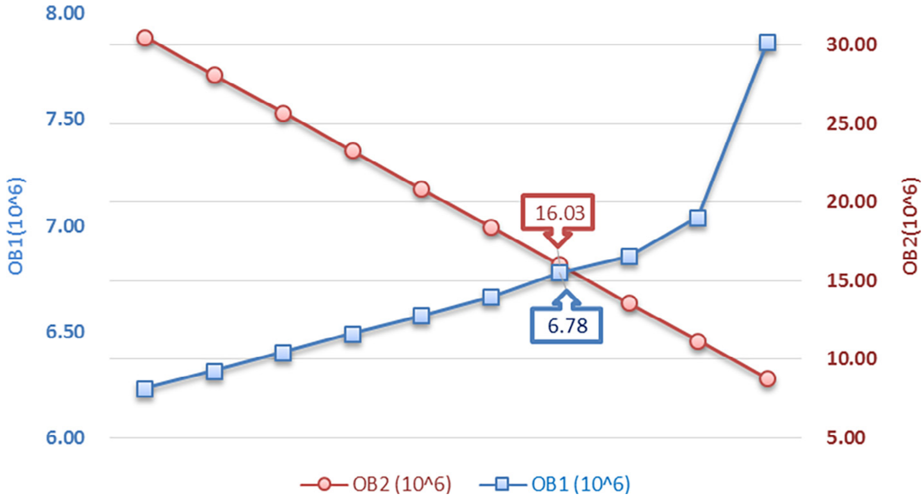

Fig. 4. The value of objectives in exact pareto set.

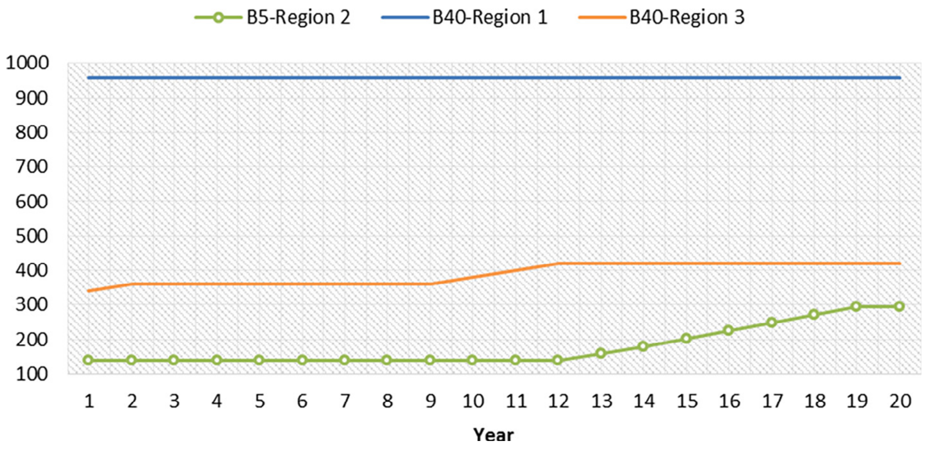

Fig. 5. The capacity of produced fuels in (Z1 = 6778417, Z2 = 16031586).

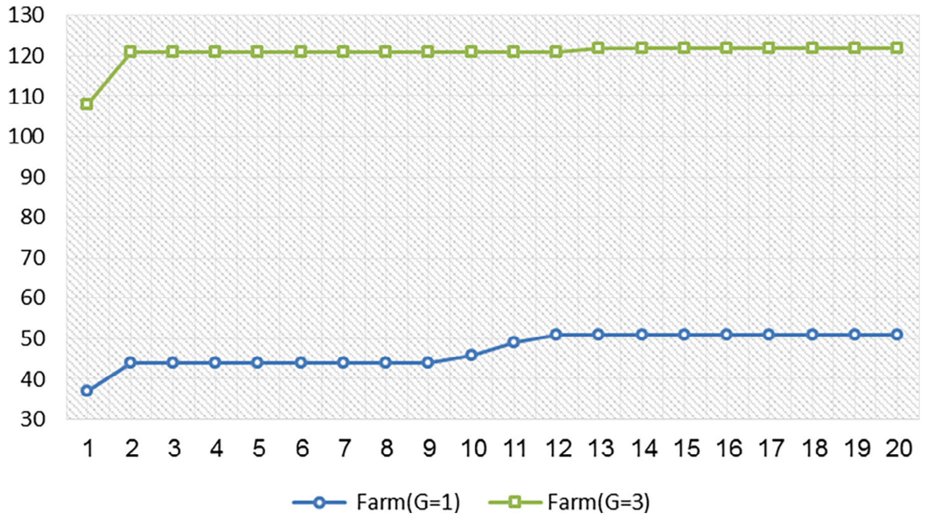

Fig. 6. Required agricultural farm area in (Z1 = 6778417, Z2 = 16031586).

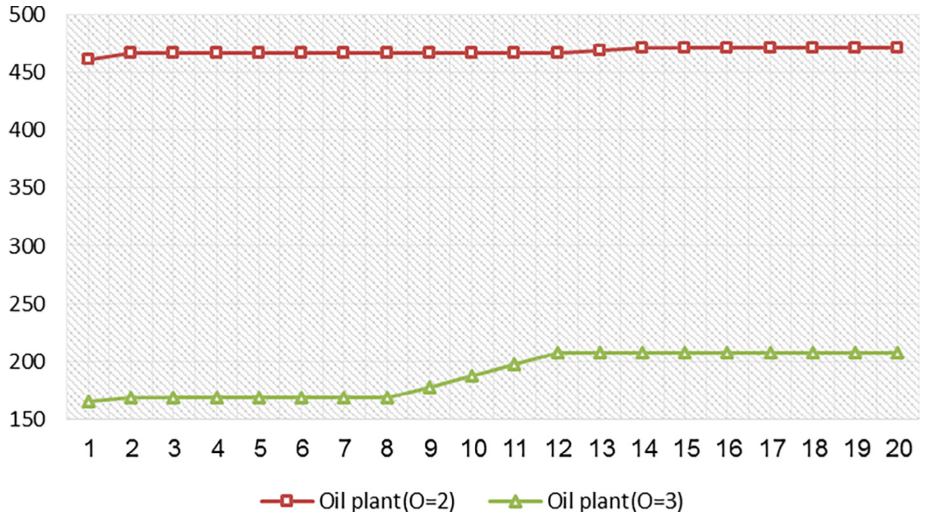

Fig. 7. Capacity of oil extraction plant in (Z1 = 6778417, Z2 = 16031586).

$$IB_{F,T} + \sum_{B} S_{B,F,T} \leq M \times \sum_{t=0}^{T-1} \sum_{K} Y_{F,K,T} \quad \forall\ F,\ T \tag{22}$$

As previously mentioned, fuel blending plants can produce different biodiesel blends. For this purpose, this study considers five fuels, namely B5, B10, B20, B40, and B100. The maximum possible quantity of produced fuels, with received biodiesel in fuel blending plant, is presented by the following equations. Based on this equation, the sum of biodiesel used for producing different biodiesel blends in a blending plant should be lower than the available biodiesel in that blending

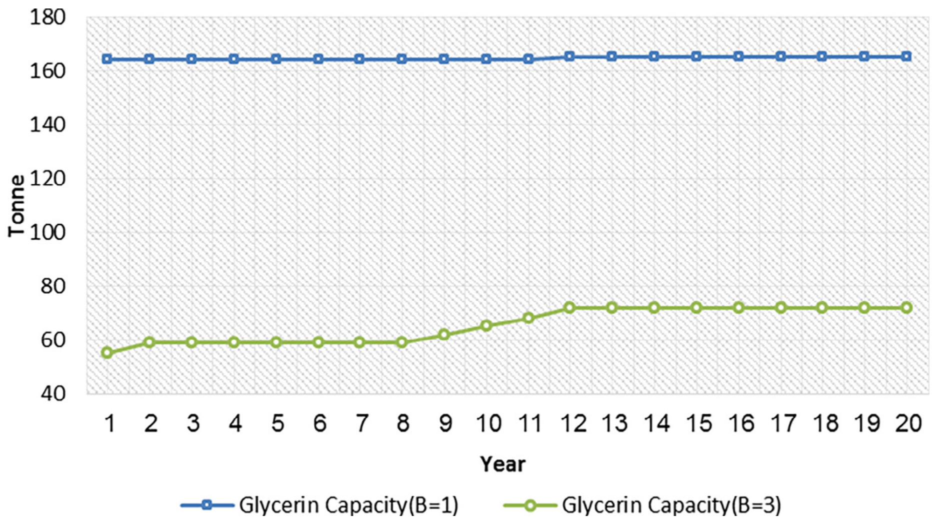

Fig. 8. Capacity of glycerin production in (Z1 = 6778417, Z2 = 16031586).

plant.

$$0.05 \times PF_{B5,F,T} + 0.1 \times PF_{B10,F,T} + 0.2 \times PF_{B20,F,T} + 0.4 \times PF_{B40,F,T} + PF_{B100,F,T} \le FF_{F,T} \quad \forall\ F,\ T \tag{23}$$

It is assumed that at any time and in any fuel blending plants, only one of biodiesel blends can be produced at the same time; Eqs. (24) and (25) explain this concept.

$$PF_{K,F,T} \le M \times V_{K,F,T} \quad \forall\ K,\ T,\ F \tag{24}$$

$$\sum_{K} V_{K,F,T} \le 1 \quad \forall\ T,\ F \tag{25}$$

Eqs. (27) to (31) calculate the quantity of consumed diesel to produce each biodiesel blend. Eq. (27) conveys that for producing one liter B5, there is a need for 0.95 L diesel. Eqs. (28)–(30) explain similar concepts for B10, B20, and B40. Moreover, Eq. (31) calculates the total diesel which is needed for producing these blends.

$$GOS_{K,F,T} \ge 0.95 \times PF_{K,F,T} \quad K = B5,\ \forall\ T,\ F \tag{27}$$

$$GOS_{K,F,T} \ge 0.9 \times PF_{K,F,T} \quad K = B10,\ \forall\ T,\ F \tag{28}$$

$$GOS_{K,F,T} \ge 0.8 \times PF_{K,F,T} \quad K = B20,\ \forall\ T,\ F \tag{29}$$

$$GOS_{K,F,T} \ge 0.6 \times PF_{K,F,T} \quad K = B40,\ \forall\ T,\ F \tag{30}$$

$$SD_{F,T} \ge \sum_{K} GOS_{K,F,T} \quad \forall\ T,\ F \tag{31}$$

Actually, according to the mentioned equations, the cost of biodiesel blends is calculated by the concept in the following equation.

$$Biodiesel\_Blend\_Cost = [(Biodiesel\_blends\_share \times Biodiesel\_Cost) + (Diesel\_share \times Diesel\_Cost)] \tag{32}$$

The relationship between the produced and the transported biodiesel blends to demand centers presented in Eq. (33). This equation conveys that the amount of fuel type K that is produced in a blending plant should be higher than the sum of fuel that is sent from that plant to different demand centers. Furthermore, Eq. (34) shows the fulfillment of demands by biodiesel fuels and diesel. Based on this equation, the demand in a center should be fulfilled by different biodiesel blends that are sent to that center from different blending plants and conventional diesel.

$$PF_{K,F,T} \ge \sum_{C} S_{F,K,C,T} \quad \forall\ F,\ K,\ T \tag{33}$$

$$GD_{C,T} + \sum_{F} \sum_{K} S_{F,K,C,T} \ge D_{C,T} \quad \forall\ C,\ T \tag{34}$$

In the following, similar concepts have been presented for the produced glycerin in the process. The produced glycerin in each biodiesel refinery is calculated by Eq. (35).

$$PGL_{B,T} \le \alpha_{gli} \times FB_{B,T} \quad \forall\ B,\ T \tag{35}$$

Eqs. (36)–(39) show relationships among the produced glycerin, the imported glycerin and the transported glycerin from each biodiesel refinery to demand center.

$$PGL_{B,T} \ge \sum_{GL} S_{B,GL,T} \quad \forall\ B,\ T \tag{36}$$

$$FGL_{GL,T} \le \sum_{B} S_{B,GL,T} \quad \forall\ GL,\ T \tag{37}$$

$$FGL_{GL,T} \ge \sum_{GLD} S_{GL,GLD,T} \quad \forall\ GL,\ T \tag{38}$$

$$\sum_{GL} S_{GL,GLD,T} + IGL_{GLD,T} \ge D_{GLD,T} \quad \forall\ T,\ GLD \tag{39}$$

The capacities of facilities have been presented in Eqs. (40)–(51). The refined waste oil, oil, biodiesel, glycerin, and fuel must be proportional to the available capacities of related facilities. Eqs. (40) and (41) are about produced oil and the capacity of oil extraction plants. Eqs. (42) and (43) show the relationships between produced biodiesel and the capacity of the biodiesel refineries. Eqs. (44) and (45) consider relationships between produced glycerin and the capacity of the biodiesel refineries. Eqs. (46) and (47) are about refined waste oil and the capacity of the waste oil refineries. The flow of glycerin to demand centers and the capacity of glycerin distributor are presented by Eqs. (48) and (49). The relationships between biodiesel blends and the fuel blending plants are calculated by Eqs. (50) and (51).

$$PO_{O,T} \le \sum_{T} CO_{O,T} \quad \forall\ O,\ T \tag{40}$$

$$CO_{O,T} \le M \times Y_{O,T} \quad \forall\ O,\ T \tag{41}$$

$$PB_{B,T} \le \sum_{T} CB_{B,T} \quad \forall\ B,\ T \tag{42}$$

$$CB_{B,T} \le M \times Y_{B,T} \quad \forall\ B,\ T \tag{43}$$

$$PGL_{B,T} \le \sum_{T} CB_{B,Gli,T} \quad \forall\ B,\ T \tag{44}$$

$$CB_{B,Gli,T} \le M \times Y_{B,T} \quad \forall\ B,\ T \tag{45}$$

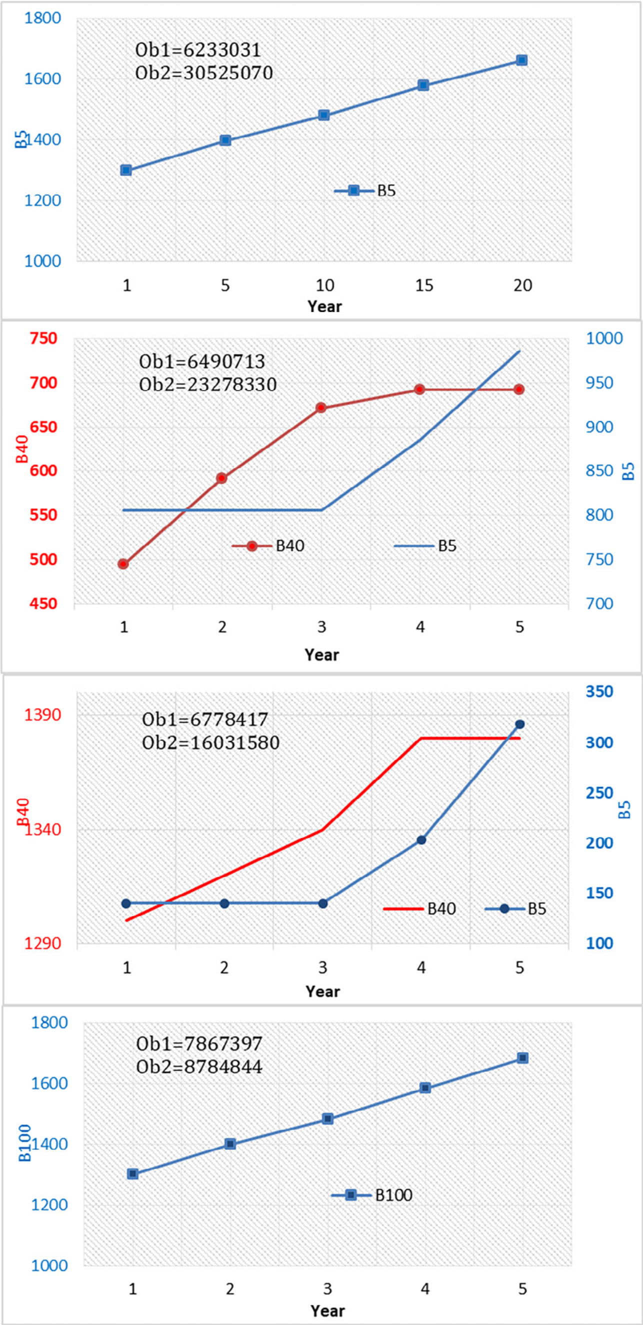

Fig. 9. The best biodiesel blends for four solutions of pareto set.

$$PRW_{W,T} \le \sum_{T} CW_{W,T} \quad \forall\ W,\ T \tag{46}$$

$$CW_{W,T} \le M \times Y_{W,T} \quad \forall\ W,\ T \tag{47}$$

$$\sum_{B} S_{B,GL,T} \le \sum_{T} CGL_{GL,T} \quad \forall\ GL,\ T \tag{48}$$

$$CGL_{GL,T} \le M \times Y_{GL,T} \quad \forall\ GL,\ T \tag{49}$$

$$\sum_{K} PF_{K,F,T} \le \sum_{t=0}^{T} CF_{F,T} \quad \forall\ F,\ T \tag{50}$$

$$CF_{F,T} \le M \times Y_{F,T} \quad \forall\ F,\ T \tag{51}$$

Numerical example

In this section, an example based on a real case study has been created and solved using an augmented ε-constraint method that it is explained by Mavrotas and Florios [35]. This method improves the conventional ε-constraint method for generating the Pareto optimal solutions. This method addresses some weak points of the conventional ε-constraint, namely, the guarantee of Pareto optimality of the obtained solution in the payoff table as well as in the generation process and the increased solution time for problems with several objective functions.

In the conventional ε-constraint method, one of the objective functions is optimized using the other objective functions as constraints, incorporating them in the constraint part of the model. In this method by parametrical variation in the RHS (e_1, e_2, …, e_p) of the constrained objective functions, the efficient solutions of the problem are obtained [36]. But this method may produce weakly Pareto optimal solutions. The augmented ε-constraint method is a method that tries to avoid this problem and accelerate the whole process. The new model for the augmented ε-constraint method becomes:

$$\mathit{Oil} + \mathit{Methanol} \rightarrow \mathit{Biodiesel} + \mathit{Glycerin}$$

In this model, S_2, … , S_p are the surplus variables of the constraints and ε is an adequately small number between 10^{-6} and 10^{-3} [36]. In this study, this method has been implemented in the GAMS environment using CPLEX solver. Table 2 shows the considered value for the indexes and Table 3 shows the value of the parameters (Table 4).

The input in this study is gathered with the help of experts in Renewable Energy and Energy Efficiency Organization (SATBA) [37] and Niroo Research Institute (NRI) [38]. Figs. 2 and 3 show the considered demands of fuel and glycerin in demand centers. It is assumed that the demands are increasing with steady gradients.

Furthermore, to calculate second objective function, there is some study that considered the emission of biodiesel and their blends [39,40]. This study uses the information of a study by Budzaky et al. [41].

Results and discussion

This section presents the model implementation results for this example. Fig. 4 shows an exact Pareto set which consists of ten points. In the ε-constraint method, different values were examined and finally, the value of 10^{-3} was chosen for ε since it led to the biggest penalty and better results. Each of these points is an exact solution for the model, and decision-makers can select their own desired point among them. As can be seen, the efforts to reduce the value of the second objective lead to exponential growth in cost objective.

As an example, one of the solutions, namely (Z_1 = 6778417, Z_2 = 16031586), and its results are described in the following. Fig. 5 presents the cumulative capacity of produced diesel blends. In this solution, B5 is produced in region 2, and B40 is produced in region 1 and region 3.

Among the crops and waste oil, the second crop, namely sunflower is the best resource for oil producing. Fig. 6 shows the required farm's area in each region. Moreover, Fig. 7 presents the capacity of the oil extraction plant in each location.

Fig. 8 shows the capacities of glycerin production facilities during the optimization period.

Furthermore, Fig. 9 indicates the optimum blends of fuels for four solutions in the exact Pareto set.

According to the results, a decrease in the second objective (environmental effects objective) leads to a higher proportion of biodiesel in the produced fuels. When (Z1 = 6233031, Z2 = 30525070) the fuel is B5. In (Z1 = 6490713, Z2 = 23278330) B40 and B5 are the best fuels, and in (Z1 = 6778417, Z2 = 16031580) B40, and B5 are selected. However, the share of B40 is more than (Z1 = 6490713, Z2 = 23278330) in this solution. Moreover, in (Z1 = 7867397,

Table 5
The value of different variables for four solutions of Pareto set in the base model.

No.	Objectives	Variables	Year				
			1	5	10	15	20
1	Z1 = 6233031	Farm usage (Cumulative) (Hectare)	20	21	22	23	24
	Z2 = 30525070	Capacity of oil plant (Cumulative) (Tonne)	78	84	89	95	97
		Capacity of Glycerin (Cumulative) (Tonne)	27	29	30.5	33	33.5
		Capacity of Waste oil refinery (Cumulative) (Tonne)	0	0	0	0	1.3
		Capacity of Glycerin supplier (Cumulative) (Tonne)	23	23	23	23	23
		Capacity of Biodiesel refinery (Cumulative) (Tonne)	65	70	74	79	82
		Used Diesel at Demand Center (Tonne/Year)	0	0	0	0	19.5
		Imported Biodiesel (Tonne/Year)	0	0	0	0	0
2	Z1 = 6490713	Farm usage (Cumulative) (Hectare)	74	86	96	99	100
	Z2 = 23278330	Capacity of oil plant (Cumulative) (Tonne)	287	334	374	388	391
		Capacity of Glycerin (Cumulative) (Tonne)	100	117	130	135	136
		Capacity of Waste oil refinery (Cumulative) (Tonne)	0	0	0	0	0
		Capacity of Glycerin supplier (Cumulative) (Tonne)	100	116	116	116	116
		Capacity of Biodiesel refinery (Cumulative) (Tonne)	238	277	309	321	323
		Used Diesel at Demand Center (Tonne/Year)	0	0	0	0	0
		Imported Biodiesel (Tonne/Year)	0	0	0	0	3
3	Z1 = 6778417	Farm usage (Cumulative) (Hectare)	146	164	169	174	174
	Z2 = 16031580	Capacity of oil plant (Cumulative) (Ton)	626	636	654	666	666
		Capacity of Glycerin (Cumulative) (Ton)	219	222	228	235	235
		Capacity of Waste oil refinery (Cumulative) (Ton)	0	0	0	0	5
		Capacity of Glycerin supplier (Cumulative) (Ton)	164	164	164	164	164
		Capacity of Biodiesel refinery (Cumulative) (Tonne)	520	528	543	561	561
		Used Diesel at Demand Center (Tonne/Year)	0	0	0	0	26
		Imported Biodiesel (Tonne/Year)	0	0	0	0	6
4	Z1 = 7867397	Farm usage (Cumulative) (Hectare)	143	143	143	143	143
	Z2 = 8784844	Capacity of oil plant (Cumulative) (Tonne)	938	938	938	938	938
		Capacity of Glycerin (Cumulative) (Tonne)	548	589	624	668	676
		Capacity of Waste oil refinery (Cumulative) (Tonne)	628	746	844	1036	1036
		Capacity of Glycerin supplier (Cumulative) (Tonne)	426	442	442	442	442
		Capacity of Biodiesel refinery (Cumulative) (Tonne)	1300	1398	1480	1580	1640
		Used Diesel at Demand Center (Tonne/Year)	0	0	0	0	0
		Imported Biodiesel (Tonne/Year)	0	0	0	0	50

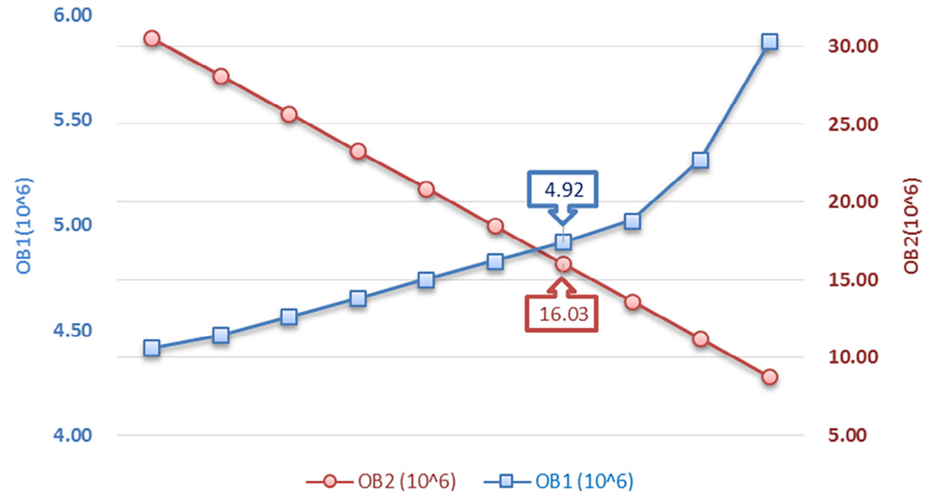

Fig. 10. The value of objectives in exact pareto set for the interest rate of 10%

Z2 = 8784844), B100 is considered as the best fuel according to conditions by the model. As it is seen in Fig. 9 and Table 7, B5 and B40 are the best biodiesel blends which are reasonable in the majority points of the Pareto set; consequently, these fuels should be considered for the gradual development of the biodiesels.

Table 5 shows the value of the decision variables. The capacity of the waste oil refinery in all solutions, except the fourth solution, is approximately zero. In other words, based on the input data, in the production of biodiesel, using crops is more economical than using waste oil; the used diesel to fulfill the considered demands is also approximately zero. Therefore, biodiesel blends fulfill most of the demands. As mentioned before, a decrease in environmental effects causes an increase in costs. Furthermore, this decrease leads to a higher proportion of biodiesel in biodiesel blends. Thus, the capacities of facilities, namely oil plant, glycerin plant, and biodiesel refinery, etc. are increased. In the fourth solution, the dimension of the farm is decreased, and the capacity of the waste oil refinery is more than other solutions.

Sensitivity analysis

This section surveys the sensitivity analysis of the results. For this

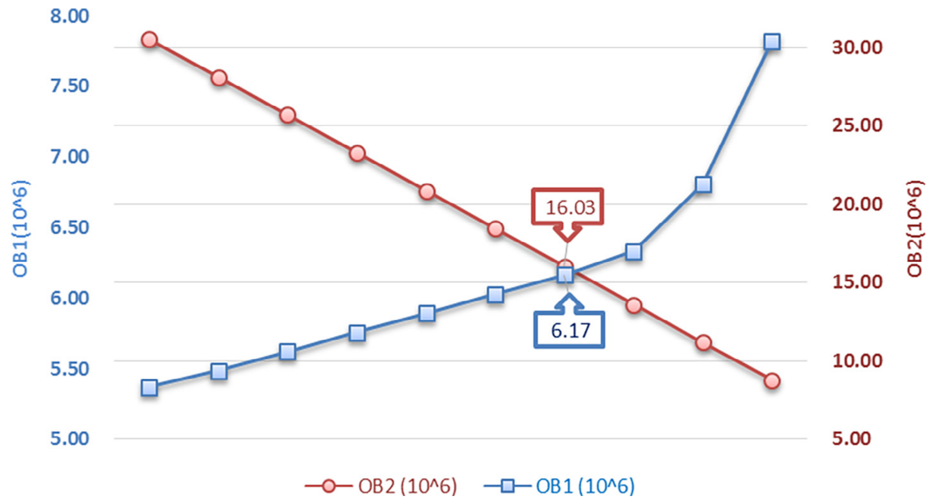

Fig. 11. The value of objectives in exact pareto set for 20% decrease in diesel price.

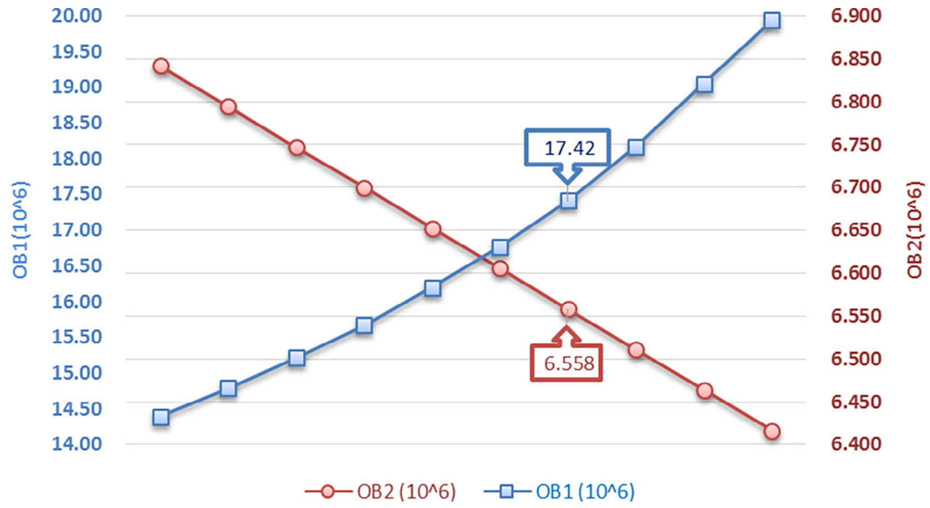

Fig. 12. The value of objectives in exact pareto set for 20% increase in diesel price.

Table 6
The value of the objective functions for the base model and three sensitivity analyses.

	Base	Interest rate (10%)	Diesel price (−20%)	Diesel price (+20%)
First Solution	Z1 = 6233031	Z1 = 4414921	Z1 = 5370001	Z1 = 14390780
	Z2 = 30525070	Z2 = 30525070	Z2 = 30525010	Z2 = 6841668
Second Solution	Z1 = 6316395	Z1 = 4476965	Z1 = 5487716	Z1 = 14792750
	Z2 = 28109490	Z2 = 28109470	Z2 = 28109430	Z2 = 6794427
Third Solution	Z1 = 6403566	Z1 = 4564246	Z1 = 5622534	Z1 = 15214450
	Z2 = 25693910	Z2 = 25693890	Z2 = 25693860	Z2 = 6747187
Fourth Solution	Z1 = 6490713	Z1 = 4653036	Z1 = 5758570	Z1 = 15674870
	Z2 = 23278330	Z2 = 23278330	Z2 = 23278290	Z2 = 6699946
Fifth Solution	Z1 = 6577613	Z1 = 4742181	Z1 = 5894627	Z1 = 16197250
	Z2 = 20862750	Z2 = 20862740	Z2 = 20862710	Z2 = 6652706
Sixth Solution	Z1 = 6664502	Z1 = 4831490	Z1 = 6030116	Z1 = 16770480
	Z2 = 18447170	Z2 = 18447160	Z2 = 18447140	Z2 = 6605466
Seventh Solution	Z1 = 6778417	Z1 = 4920858	Z1 = 6166085	Z1 = 17416950
	Z2 = 16031580	Z2 = 16031580	Z2 = 16031560	Z2 = 6558225
Eighth Solution	Z1 = 6856997	Z1 = 5023027	Z1 = 6333143	Z1 = 18173990
	Z2 = 13616000	Z2 = 13616000	Z2 = 13615990	Z2 = 6510985
Ninth solution	Z1 = 7038972	Z1 = 5313880	Z1 = 6806396	Z1 = 19049670
	Z2 = 11200420	Z2 = 11200420	Z2 = 11200410	Z2 = 6463744
Tenth Solution	Z1 = 7867397	Z1 = 5874861	Z1 = 7821783	Z1 = 19936240
	Z2 = 8784844	Z2 = 8784844	Z2 = 8784838	Z2 = 6416504

Table 7
The best biodiesel blends for the base model and three sensitivity analyses.

	Base	Interest rate (10%)	Diesel price (−20%)	Diesel price (+20%)
First Solution	B5	B5	B5	B100
Second Solution	B5, B40	B5, B40	B5, B40	B100
Third Solution	B5, B40	B5, B40	B5, B20, B40	B100
Fourth Solution	B5, B40	B5, B40	B5, B40	B100
Fifth Solution	B5, B40	B5, B40	B5, B40	B100
Sixth Solution	B5, B40	B5, B40	B5, B40	B100
Seventh Solution	B5, B40	B5, B40	B5, B40	B100
Eighth Solution	B40, B100	B40, B100	B40, B100	B100
Ninth solution	B40, B100	B40, B100	B40, B100	B100
Tenth Solution	B100	B100	B100	B100

purpose, the effects of changes in the interest rate and diesel price are considered. Fig. 10 shows the sensitivity analysis of the results for the interest rate. Results show that an increase in the interest rate to 10% causes a decrease in the first objective in comparison to 5% interest rate.

Figs. 11 and 12 show the sensitivity analysis of exact Pareto set concerning diesel price.

Table 6 shows a summary of these exact Pareto sets.

Table 7 presents the produced biodiesel fuels for each of the solutions.

Based on the results of the sensitivity analysis, a decrease in the diesel price and an increase in the interest rate, do not cause any change in the combination of produced fuels; however, a 20% increase in diesel price leads to the production of B100.

Conclusion

In this paper, a comprehensive study is carried out with the aim of biodiesel development using a multi-objective and multi-period MIP model. The objectives of the model are the minimization of costs and environmental effects, and the study uses an augmented e-constraint method to get the exact Pareto set. The main aims of this study are to select the best primary resources among waste oil and different crops as well as the best fuels among B5, B10, B20, B40, B100, and diesel to fulfill fuel demands during an optimization period. The model selects the best fuels and the capacities of facilities according to the conditions. The results show that the objectives are in conflict with each other and a reduction in environmental effects leads to an increase in costs. Furthermore, it causes the use of a higher biodiesel proportion in the produced fuels. For example, in the best value for environmental effects, B100 is selected, but in the worst value, B5 is considered as the best fuel. Moreover, at the midpoints of exact Pareto set, the combination of several biodiesel blends are selected; for instance, in the point of (Z1 = 6778417, Z2 = 16031580) B40 and B5 are selected as the best fuels by the model. All in all, the results demonstrate that B5 and B40 are the best biodiesel blends that are reasonable in most of the points. Consequently, these fuels should be considered for the gradual development of the biodiesels.

The biodiesel is more expensive than conventional fuels like fossil fuels in most countries; therefore, replacing conventional fuels with biodiesel blends is difficult. However, fuels with a higher biodiesel proportion release less pollution. On the other hand, due to climate change and global warming and its international commitments, a gradual tendency towards cleaner fuels seems a rational decision. Based on the obtained results through this study, the presented model can help decision-makers for designing a development plan considering the future requirements and restrictions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2019.100545.

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