Optimal design and planning of biodiesel supply chain considering non-edible feedstock

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Abstract

The rapid expansion of first-generation biodiesel production from vegetable edible oils and animal fats has triggered a sense of concern among policymakers and development practitioners about farm land allocation, food supply, and food market equilibrium. In this respect, utilization of second-generation biodiesel from non-edible feedstocks has been attracted many interests in recent years. To accelerate transition towards large-scale and economic viable biofuels, systematic design and optimization of entire biofuel supply chains is crucial. In this paper, firstly the presented works for biofuel supply chains optimization are systematically reviewed and categorized. Secondly, a multi-period and multi-product biodiesel supply chain network design model is developed. The proposed model is capable to determine the optimum numbers, locations, capacity of facilities, suitable transportation modes, appropriate technology at bio-refinery, material flow, and production planning in different periods. The proposed model is applied in a real case in Iran. We consider *Jatropha* seeds and waste cooking oil as non-edible feedstocks for second-generation biodiesel production in the studied case. The acquired results demonstrate the efficiency and performance of the proposed model in designing biodiesel supply chain network.

Key words: Biodiesel supply chain optimization; Non-edible feedstocks; *Jatropha*; Waste cooking oil; Sustainable development

1. Introduction

In recent years, concerns about energy security, food crisis, environmental issues, and standards of living have led to search for renewable and cleaner sources of energy. Among various sectors demanding energy, transportation sector consumes significant amount of energy

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1 which in turn causes to fossil fuel depletion and environmental pollution (khan et al., 2014). In
2 response to urgent need for cleaner and renewable energy in transportation sector, researchers,
3 policymakers and development practitioners have introduced biofuels utilization in large-scales
4 from biomass, forestry residues, energy crops, waste oils, and municipal wastes (Hamelinck et
5 al., 2005; Bai et al., 2012). In this respect, China has built up more than 2000 biodiesel
6 production factories by 2007 (Yang et al., 2012). U.S. has targeted to produce 36 billion gallons
7 of biofuels by 2022 (Yue et al., 2014).

8 Bioethanol and biodiesel have been recognized as promising biofuels providing
9 sustainable and viable solution to the mentioned problems. Bioethanol is produced from the
10 feedstocks containing glucose, cellulous, and starch such as sugar cane, wheat, corn, sorghum,
11 cassava, sugar beet, wood chips, and rice straw (You et al., 2012). Biodiesel is produced from
12 oleaginous feedstocks such as soybean, palm, sunflower, castor, cotton, rapeseed, and Jatropha
13 (Pandey, 2008). Currently, most of feedstocks used for biodiesel production are provided from
14 vegetable oils and animal fats which have edible nature (khan et al., 2014).

15 The rapid increase of the biofuel industry implies a large amount of agricultural crops
16 affecting farm land allocation, feedstock and food market equilibrium, food supply and
17 agricultural development in rural areas (Bai et al., 2012). In Malaysia utilizing edible palm oil for
18 biodiesel production has risen price of palm cooking oil by 70 percent (Tenenbaum, 2008).
19 Another problem arising from biodiesel production from edible feedstocks is related to biodiesel
20 commercial feasibility. Indeed, high edible feedstocks' prices for biodiesel production needs
21 remarkable amount of subsidies granted by governmental policymakers to be comparable with
22 fossil diesel in energy markets. It is worthy to note that feedstock costs comprise about 80% of
23 biodiesel total production costs (Wen et al., 2010; Pandey, 2008). To deal with food supply

1 concerns and high prices of edible feedstocks for biodiesel production, researchers have found
2 new sources of biofuel feedstocks such as Jatropha and waste cooking oil that have non-edible
3 nature and don't compete with food crops to seize fertile lands (Chhetri et al., 2008). Biodiesel
4 production from non-edible oil would help to biodiesel feasibility without granting subsidies and
5 lead to food supply improvement.

6 Jatropha plant is the most promising non-edible energy crop which has attracted many
7 interests due to high oil content for biodiesel production, perennial drought tolerant, soil
8 reclamation, desert reduction, rural development and environmental benefits (Achten et al.,
9 2008).

10 Jatropha seed kernel has high oil content circa 30–40% (Pandey et al., 2012). After palm,
11 Jatropha has the highest oil content among edible and non-edible energy crops. Biodiesel
12 produced from Jatropha has low acidity and good oxidation ability compared to soybean oil, low
13 viscosity compared to castor oil and better cooling properties compared to palm oil (Tapanes et
14 al., 2008). Jatropha is carbon neutral due to existing balance between the amount of carbon
15 dioxide emitted from the corresponding biodiesel combustion and the amount of carbon dioxide
16 absorbed by agro-forestry of Jatropha. As now, successful utilization of Jatropha for biodiesel
17 production in large scales have been reported in Malaysia, Indonesia, and India (Juan et al.,
18 2011; Silitonga et al., 2011; Kumar et al., 2012). It is expected that about 1.72 million hectares of
19 land would be allocated for Jatropha cultivation in India (khan et al., 2014). Notably, although
20 other non-edible feedstocks such as Sal, Mahua, Neem, and Pongamia have been specified for
21 biodiesel production, the following features make Jatropha plant prominent respect to other ones
22 (Jain and Sharma, 2010).

According to the literature, the main contributions of *Jatropha* could be stated as follows (Jongschaap et al., 2007; Sharma and Sarraf, 2007; Achten et al., 2008; Dermibas, 2008; Jain and Sharma, 2010; Brittain and Litaladio, 2010; Pandey et al., 2012):

- Growth in marginal lands and soil reclamation
- Preventing soil erosion and improving water infiltration
- Drought tolerant and low water and nutrient requirement
- High seed oil content with good quality for biodiesel production
- Reduction of greenhouse gas effects
- Opportunity for rural poor areas and contribution to poverty reduction
- Useful by-products used as manure, hygienic and medicinal material production
- High resistance against pests and diseases
- Do not compete with food supply

Transesterification process is commonly used for converting the oleaginous feedstock to biodiesel (Gerpen, 2005). The most important by-product of transesterification process is glycerin which is widely used in hygienic and medicinal industries. Biodiesel is usually blended with fossil diesel with specified blends for example B2 to B20 to improve its combustion and reduce its destructive environmental effects. B20 blend means blending 20% biodiesel with 80% petro-diesel. Blending biodiesel and diesel up to 20 percent (B20) does not need any modification in the current diesel engines (Parawira, 2010).

Another interesting non-edible feedstock for biodiesel production is waste cooking oil (Zhang et al., 2003). Utilizing waste cooking oil for biodiesel production provides good feedstock and helps to solve its disposal problem. Edible oils are vastly used for cooking in homes and restaurants, and also for different food production in corresponding factories. About

1 25% of these oils are lost as waste. This amount of waste should be disposed and could not be
2 recovered to be used for cooking purposes. Therefore, suitable planning helping to collect and
3 utilize these used oils provides an appropriate feedstock for biodiesel production with very low
4 price (Tan et al., 2011).

5 Supply chain network design (SCND) problem is related to strategic level decisions
6 affecting on overall performance of supply chain management (Babazadeh et al., 2013). The
7 main concerns in a SCND problem are determining the numbers, locations, capacity of locations,
8 and material flows (Andersen et al. 2012; Babazadeh and Razmi, 2013). Also, production
9 planning decisions such as amount of production and inventory level in different periods, which
10 are categorized as tactical level decisions, may be integrated with the strategic level decisions to
11 prevent sub-optimal solutions. Meanwhile, integrated models have higher complexity and thus
12 need more computational efforts than separated ones (Babazadeh et al., 2014). Recently, rapid
13 extension of biofuel industry has encouraged researchers to study biofuel supply chain through
14 developing optimization mathematical models (An et al., 2011a). An et al. (2011a) note that
15 determining the optimal structure of a biofuel supply chain from feedstocks sources to final
16 biofuel consumers will significantly help to commercial feasibility of biofuels.

17 In this study, firstly, the recently presented mathematical models for optimizing biofuel
18 supply chains (SCs) are reviewed and systematically categorized to explore the literature gaps.
19 Secondly, motivated from the shortcomings from the literature an integrated mixed-integer linear
20 programming (MILP) model for designing biodiesel supply chain network is developed to
21 optimize the related strategic and tactical level decisions. In the proposed model, strategic level
22 decisions are attributed to determining the numbers and locations of facilities in each echelon of
23 the SC and their capacities, transportation mode, and production technology in bio-refineries.

1 Tactical level decisions are related to production planning decisions including the amount of
2 production and inventory levels in different periods and the amount of material transported
3 between different echelons in different periods. The proposed model consists of five echelons
4 including feedstock centers, collection and preprocessing centers, bio-refineries, distribution
5 centers, and customer zones. The model is applied in a real case in Iran for 10 years planning
6 horizon.

7 The body of this paper is structured in 5 sections. In Section 2, the recently presented
8 mathematical models for designing biofuel supply chain network are reviewed and
9 systematically categorized. The concerned biodiesel supply chain network design model,
10 inspired by a real case in Iran, is described and formulated in Section 3. The proposed model is
11 implemented in a real case in Iran and the acquired results are discussed in Section 4. Finally,
12 Section 5 concludes this paper and presents some useful managerial implications and future
13 research directions.

14 2. Literature review

15 In this section the most recent studies in biofuel SCs optimization are reviewed and
16 systematically categorized to clearly show the literature gap and open practical future research
17 directions. As now, many researchers have studied SCND problem for variety of industries
18 (Melo et al., 2009). Biofuels supply chain network design extensions return back to the recent
19 decade along with increasing international attentions for biofuel utilization. An et al. (2011a)
20 presented a comprehensive review covering strategic, tactical, and operational levels in biofuel
21 SCs. Moreover, the biofuel supply chain models are classified according to upstream, midstream,
22 and downstream levels in biofuel supply chain management. They mentioned that first-
23 generation biofuels with edible feedstocks are being replaced by second-generation biofuels with

1 non-edible feedstocks such as Jatropha. [Yue et al. \(2014\)](#) reviewed and described the key
2 challenges and opportunities in modeling and optimization of biofuel SCs. In addition to
3 reviewing operational to strategic time frame decisions in biofuel SCs, integration of current bio-
4 refineries with fossil fuel refineries are investigated. Moreover, sustainability issues i.e.
5 economic, environmental and social aspects of biofuels and the approaches dealing with
6 uncertainty of biofuel supply chain are studied.

7 [Banos et al. \(2011\)](#) reviewed different optimization methods including mathematical
8 programming methods, approximate methods, heuristic and meta-heuristic methods applied to
9 renewable and sustainable energy field. [Hoekman et al. \(2012\)](#) studied composition, properties,
10 and specifications of different types of biodiesel produced from vegetable oils and animal fats.
11 [Sajjadi et al. \(2016\)](#) presented a comprehensive review on properties and specifications of
12 biodiesel produced from edible and non-edible vegetable oils. They Also studied different
13 prediction models presented to quantify biodiesel specifications. [Datta and Mandal \(2016\)](#)
14 investigated production, performance and emissions from a compression ignition engine using
15 biodiesel. [Verma and Sharma \(2016\)](#) studied the various technical aspects of biodiesel
16 production methodology and determined the optimum ranges for parameters of biodiesel
17 production process. [Gold and Seuring \(2011\)](#) reviewed the supply chain and logistics issues of
18 bioenergy production from the works published from 2000 to 2009. They note that biofuel
19 feedstock costs and continuous feedstock supply are the main concerns in biofuel supply chain
20 management.

21 Generally, biofuel SCs comprise five major echelons including biomass production
22 centers, collecting and processing centers, biofuel production centers, biofuel distribution
23 centers, and biofuel consumers ([Gold and Seuring, 2011](#)). Also, logistic systems are required for

1 creating material flow between different echelons within the network. Integrating all echelons in
2 a unique model prevents sub-optimal solutions, but increases the degree of complexity of the
3 model. The main important and affective decisions which should be determined by a biofuel
4 supply chain network design model are as follows: the optimum numbers and locations of
5 facilities in each echelon, capacities of established facilities in each echelon, technology options,
6 appropriate logistics and transportation modes, and optimal material flow between different
7 echelons. In addition, due to seasonal availability of biomass, considering the biofuel SCs under
8 dynamic conditions will lead to results being more compatible with real world assumptions. In
9 other words, multi-period biofuel SCs provide appropriate decision making about the amount of
10 production in each period and required inventory which should be stored to deal with discrete
11 yielding of biomass throughout the year.

12 Exploring the literature shows that most of biofuel supply chain models have been
13 presented for the first-generation biofuels utilization ([Zamboni et al., 2009a](#); [Zamboni et al., 2009b](#); [Corsano et al., 2011](#); [Akgul et al., 2011](#)). However, developing first-generation biofuels
14 will intensify food crisis at worldwide. In contrast, some researchers have tried to study second-
15 generation biofuels production from residues and non-edible energy crops ([Huang et al., 2010](#);
16 [Chen and Fan, 2012](#); [Čuček et al., 2010](#)). Moreover, some researchers consider hybrid first and
17 second-generation biofuels and land competition for harvesting edible and non-edible feedstocks
18 ([Andersen et al., 2012](#)).

19 It should be noted that although the superstructure of the biofuel SCs is similar to
20 traditional SCs (i.e., suppliers, production, and distribution centers), significant differences
21 among the operating systems make biofuel SCs unique and therefore specific modeling is
22 required. For example, in traditional SCs, suppliers are commonly omitted in integrating SC
23

1 echelons ([Melo et al., 2009](#)) while supply centers integration with other echelons is critical in
2 biofuel SCs optimization ([Andersen et al., 2012](#)). Indeed, in traditional SCs, suppliers are
3 available throughout the year, but in biofuel SCs, feedstock availability is seasonal and
4 dependent on weather condition. Additionally, while reverse logistics and recovering end-use
5 products are interested in traditional SCs ([Pishvaei et al., 2014](#)), this option is not possible in
6 biofuel SCs.

7 At the following, we study the main features of biofuel SCs from the recent publications.
8 We focus on strategic and tactical level decisions investigated by researchers. Strategic level
9 decisions are long-term decisions that have an influence over years and decades ([Yue et al.,](#)
10 [2014](#)). Tactical level decisions relate to mid-term planning horizon and usually take place for 3
11 to 18 months ([GhasemyYaghin et al., 2012](#)).

12 [Table 1](#) shows the classification codes used for specifying the properties of the biofuel
13 supply chain networks. [Table 2](#) demonstrates the properties of the recently presented works in
14 the literature. In this Table, the presented models are classified according to planning horizon,
15 different echelons, modeling properties, uncertainty, output decisions, and objective function
16 types. It is worthy to note that we have presented some additional codes in [Table 1](#) and [Table 3](#)
17 which have not addressed in the investigated works, but are the components studied in traditional
18 SCs and may be addressed in future studies.

19 With respect to uncertainty control in biofuel SCs, some researchers have developed
20 efficient models under uncertainty. Overall, uncertainty of biofuel SCs could be classified in
21 three categories including supply uncertainty, process uncertainty, and demand uncertainty. In
22 supply uncertainty classification, uncertainty of the upstream of biofuel SC i.e. from supply
23 centers to bio-refineries is considered. In this respect, changes in weather conditions and amount

of yields are the most important factors to be considered under uncertainty. Cundiff et al. (1997) considered the uncertainty of biomass delivery design problem through defining discrete scenarios for weather conditions. In process uncertainty taxonomy, uncertainty of midstream biofuels SCs (i.e., bio-refineries) and transportation costs are taken into account. In demand uncertainty group, changes in demand of customers are considered. Kim et al. (2011a) addressed all three uncertainty types in biofuel SCs optimization. However, they used sensitivity analysis method to deal with the uncertainty. This method is not a comprehensive method for dealing with the uncertainty. Totally, stochastic programming approaches (Pishvae et al., 2009), possibilistic programming approach (Pishvae and Torabi, 2010), and robust optimization methods (Babazadeh et al., 2014) are commonly used approaches to efficiently confront the uncertainty of SCs. Table 3 illustrates the codes of modeling types existing in the literature. Table 4 investigates the presented models based on modeling aspects, solution methods, and studied case.

Table 1. Classification codes of the Biofuel supply chain networks

Planning Horizon	Code	Output decisions	Code
Long-term (Strategic)	Str	Location/allocation	L
Mid-term (Tactical)	Ta	Capacity of facilities	CF
Network layers		Number of facilities	NF
<i>Forward layers</i>		Flow amount	FA
Supplier centers	SC	Inventory	I
Collection centers	CC	Transportation mode	TM
Production centers	PC	Type of Technology	T
Distribution centers	DI	Number of vehicles	NV
Customers	CU	Objectives	
Problem properties		<i>Economic objectives</i>	
<i>Facility capacity</i>		Min cost/Max profit	C
Capacitated	Ca	Max responsiveness	R
Uncapacitated	UC	Max demand satisfaction	S
<i>Products</i>		Risk minimization	RI
Single-product	SP	<i>Environmental objectives</i>	
Multi-product	MP	Min environment impact	EI
<i>Periods</i>		Max resource conservation	RC
Single-period	SPr	<i>Social objectives</i>	
Multi-period	MPr	Max employment opportunity	E
Uncertainty		Max local development	LD
Supply uncertainty	US	Min Product risk	PR

Process uncertainty UP
Demand uncertainty UD

Min work hazard

W

Table 2. Properties of the biofuel supply chain networks

Article	Horizon	Layers	Properties	Uncertainty	Output	Objectives
Cundiff et al. (1997)	Ta	SC, CC, PC	Ca, MPr	US	CF, FA	C
Tan et al. (2009)	Ta	SC, PC	Ca, MP, MPr	US, UD	FA	EI
Čuček et al. (2010)	Str, Ta	SC, PC	Ca, MP	-	L, NF, FA, T	C, EI
Huang et al. (2010)	Str, Ta	SC, PC, CU	Ca, MP, MPr	-	L, NF, CF, FA	C
An et al. (2011b)	Str, Ta	SC, CC, PC, DI	Ca, MP, MPr	-	L, T, CF, FA	C
Papapostolou et al. (2011)	Str, Ta	SC, PC	Ca, MP, SPr	-	FA	C
Kim et al. (2011a)	Str, Ta	SC, PC, CU	Ca, MP, SPr	US, UP, UD	L, NF, FA, T, CF	C
Kim et al. (2011b)	Str, Ta	SC, PC, CU	Ca, MP, SPr	-	L, NF, FA, T, CF	C
Dal-Mas et al. (2011)	Str, Ta	SC, PC, CU	Ca,MP,MPr	US, UD	L, NF, FA, CF, NV, TM	C
Giarola et al. (2011)	Str, Ta	SC, PC, CU	Ca, MP, MPr	-	L, NF, FA, T, CF, TM	C, EI
Leão et al. (2011)	Str, Ta	SC, CC, PC	Ca, SP, MPr	-	L, NF, FA, T, CF	C
Andersen et al. (2012)	Str, Ta	SC, PC, DI,	Ca, MP,MPr	-	L, NF, CF, FA, I, NV	C
Judd et al., (2012)	Str, Ta	SC, CC	Ca, SP, SPr	-	L, I, FA, NV	C
Chen and Fan (2012)	Str, Ta	SC, PC, DI, CU	Ca, MP, SPr	US, UD	L, NF, FA, CF	C
Ng et al. (2013)	Str, Ta	SC, PC,	Ca, MP	-	L, CF, FA	C
Ebadian et al. (2013)	Str, Ta	SC, CC, PC	MP, MPr	US	L, I, FA	C
Osmani and Zhang (2013)	Str, Ta	SC, PC, CU	Ca, MP, SPr	US, UD	L, CF, FA	C
Srinivasan and Malliga (2013)	Str	CC	SP, SPr	-	L	C
Santibañez-Aguilar et al. (2014)	Str, Ta	SC, PC, DI, CU	Ca, MP, MPr	-	CF, L, NF, FA, TM, NV, T	C, EI, E
Our work	Str, Ta	SC, CC, PC, DI, CU	Ca, MP, MPr	-	L, NF, FA, CF, NV, TM, T	C

Table 3. Codes of modeling type

Modeling	Code
Linear programming	LP

Integer Programming	IP
Mixed integer linear programming	MILP
Mixed integer non-linear programming	MINLP
Mixed integer goal programming	MIGP
Scenario based stochastic mixed integer programming	SSMIP
Fuzzy programming	FP
Scenario-based mixed integer robust optimization	SMIRO
Uncertainty set based mixed integer robust optimization	UMIRO

Table 4. Modeling type and solution method

Article	Modeling	Solution method	Case study-Country
Cundiff et al. (1997)	LP	Commercial solver	Biomass supply- Piedmont county, U. S.
Tan et al. (2009)	FP	Max-min fuzzy solution	Hybrid bioethanol and biodiesel-Philippine
Čuček et al. (2010)	MILP	Commercial solver	Biomass supply- Central European
Huang et al. (2010)	MILP	Commercial solver	Biomass supply- California, U. S.
An et al. (2011b)	MILP	Commercial solver	Biomass supply- Central Texas, U. S.
Papapostolou et al. (2011)	LP	Commercial solver	First-generation biofuel- Greece
Kim et al. (2011a)	SMILP	Commercial solver - Mont carlo simulation and global sensitivity analysis	Bioethanol- U. S.
Kim et al. (2011b)	MILP	Commercial solver	Hybrid bioethanol and biodiesel- U. S.
Dal-Mas et al. (2011)	SMILP	Scenario-based stochastic programming	Ethanol- Italy
Giarola et al. (2011)	MILP	ϵ -constraint	Hybrid first and second-generation Bioethanol- Italy
Leão et al. (2011)	MILP	Commercial solver	Biodiesel-Brazil
Andersen et al. (2012)	MILP	Commercial solver	Biodiesel- Argentina
Judd et al., (2012)	MILP	Two stage decomposition	Cellulosic ethanol- Central Virginia, U. S.
Chen and Fan (2012)	SMILP	Progressive hedging (PH) method based on Augmented Lagrangian	Ethanol- California, U. S.
Ng et al. (2013)	MINLP	Commercial solver	Biodiesel- Malaysia
Ebadian et al. (2013)	MILP	Commercial solver - simulation	Cellulosic ethanol- Canada
Osmani and Zhang (2013)	SMILP	Discretizing continuous probability to scenarios and solving with Commercial solver	Ligno-cellulosic ethanol- U. S.
Srinivasan and Malliga (2013)	IP	Myopic and exchange heuristics	Jatropha warehouse location- India
Santibañez-Aguilar et al. (2014)	MILP	ϵ -constraint	Biofuel- Mexico

Our work	MILP	Commercial solver	Biodiesel-Iran
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From the above-mentioned classification, the following statements could be concluded about literature gaps:

- Although most of studies have integrated strategic and tactical level decisions in modeling, they have neglected horizontal integration of biofuel SCs i.e. from supply centers to consumers. As mentioned before, this inattention would lead to sub-optimal solutions. Also, in order to reduce computational complexity of the models, output decisions have been limited to location, capacity and material flow and other important decisions related to technology options, transportation modes, and production planning have been omitted.
- Most of models consider multi-period and multi-product conditions for capacitated facilities in biofuel SC design. These assumptions are compatible with real world practices.
- While uncertainty is integral part of real world biofuel SCs, this issue has been scarcely addressed by researchers.
- Cost criterion are the most interesting objective function investigated by researchers. However, other environmental and social aspects of biofuel SCs have been scarcely evaluated.
- Most of case studies have been developed in European and American countries. Although there is a great potential for biofuel utilization in Asia, very few works have been developed for designing biofuel SC in this continent.

In current work, we present a comprehensive model covering the gaps related to modeling aspects in the literature. Really, our model integrates biodiesel SC from supply centers' tier to

1 consumers' tire considering the most important decisions related to location, capacity, material
2 flow, technology option, transportation mode, and production planning. Also, we implement the
3 model in a real case in Iran. The last row of [Tables 2](#) and [4](#) illustrates the main differences of our
4 work with those existing in the literature.

3. Problem description and formulation

5
6
7 In this paper, the biodiesel supply chain network design problem is considered for a real
8 case in Iran. The considered biodiesel SC network is a multi-product and multi-period network
9 that includes five echelons: (1) feedstock centers, (2) collection and preprocessing centers, (3)
10 bio-refineries, (4) distribution centers, and (5) customer centers. The required non-edible
11 feedstocks are collected from supply centers and preprocessed in collection and preprocessing
12 centers. We consider *Jatropha* seeds and waste cooking oils as non-edible feedstocks. Since
13 operating systems for collecting *Jatropha* seeds and waste cooking oils are thoroughly different,
14 we consider separated collection and preprocessing centers for each feedstock. Extracted
15 *Jatropha* seed oil and filtered waste cooking oil are transported to bio-refineries from
16 corresponding collection and preprocessing centers. Biodiesel and glycerin are produced from
17 received oils in bio-refineries. Biodiesel is sent to distribution centers, but glycerin is directly
18 shipped to related customer zones. Customer demands for biodiesel are supplied from
19 distribution centers. Inventory holding as safety stocks is possible in collection and
20 preprocessing centers, bio-refineries, and distribution centers. [Gold and Seuring \(2011\)](#)
21 mentioned that inventory holding throughout biofuel supply chain from feedstock centers to
22 consumer centers is essential to adequately match feedstock supply and biofuel demand. The
23 underlying structure of the considered biodiesel SC network is illustrated in [Figure 1](#).

Fig. 1. The structure of the considered biodiesel SC network

All used parameters are known and deterministic. Only customer zones and supply centers of waste cooking oil are known, but other locations should be determined among the candidate locations. According to the features of the studied case, two transportation modes namely road and rail modes are assumed for transporting different materials within the network. Biodiesel production processes can be distinguished into two general types. The first type which is the most commonly used in this industry is batch method (Meher et al., 2006; Peterson et al., 2002). The second type is based on continuous systems (Peterson et al., 2002). Cold fusion reactor is widely used in continuous systems (Iran Biodiesel Kish Co.). The first technology has lower fixed cost but higher variable cost than second one (Iran Biodiesel Kish Co.). The model selects the suitable biodiesel production technology at each bio-refinery from these two alternatives. Since Jatropha plants yield after two years of cultivation, it is assumed that facilities should be constructed in these two years to be utilized once Jatropha farms commence to yield. We assume arid and semi-arid areas as candidate locations for Jatropha cultivation. Planning horizon is 10 years and each season is considered as a time period. Therefore, there would be 40 periods in planning horizon.

From the strategic point of view, the decisions to be addressed by the proposed model under the above assumptions include determining the optimum numbers, locations and capacities of Jatropha cultivation centers, collection and preprocessing centers for Jatropha seeds and waste cooking oil, bio-refineries, and distribution centers, and suitable technology option at each established bio-refinery. From the tactical point of view, the decisions to be addressed include the amounts of production, inventory levels, aggregate material flow between network nodes, and suitable transportation modes in different periods. Our motivation for such integration is to avoid sub-optimal solutions resulted due to separated decision making for tactical and strategic level decisions (Shen, 2007). In addition, in the proposed model, capacity of facilities is determined through continuous decision variables to avoid additional variable costs. Notably, some studies assume binary variables for determining the capacity of facilities (Pishvae et al., 2012) which lead to selecting facilities with more capacities than that is required.

3.1. Formulation of the proposed biodiesel SC network

Shortly, the verbal description of the proposed biodiesel SC network design model is shown as below. The objective function minimizes net present value (NPV) of total costs.

Minimization of total cost = NPV (Fixed opening costs + Variable opening costs + Production costs + Inventory holding costs + Transportation costs)

Subject to:

- Demand and supply satisfaction constraints
- Production balance equations
- Inventory balance equations
- Capacity expansion constraints
- Production and inventory capacity constraints
- Non-negativity and binary limitations on related decision variables.

- 1 The following sets, parameters, and variables are used in formulation of the concerned biodiesel
- 2 supply chain network.

Sets

f	Set of candidate locations for Jatropha cultivation centers
g	Set of candidate locations for supply centers of waste cooking oil
i	Set of candidate locations for collection and preprocessing centers of Jatropha seeds
s	Set of candidate locations for collection and preprocessing centers of waste cooking oil
j	Set of candidate locations for bio-refinery centers of biodiesel production
k	Set of candidate locations for distribution centers of biodiesel
m	Set of customer centers of biodiesel
n	Set of customer centers of glycerin
l	Set of transportation mode
r	Set of different technologies available for biodiesel production
t	Set of time period

Parameters

D_{mt}	Demand of customer center m for biodiesel in period t
DE_{nt}	Demand of customer center m for glycerin in period t
WO_{gt}	Amount of waste cooking oil supplied by center g in period t
LA_f	Minimum land area dedicated for Jatropha cultivation center at location f
UA_f	Maximum land area available for Jatropha cultivation center at location f
LC_i	Lower bound dedicated on capacity of collection and preprocessing center of Jatropha seeds at location i
UC_i	Upper bound of capacity of collection and preprocessing center of Jatropha seeds at location i
LW_s	Lower bound dedicated on capacity of collection and preprocessing center of waste cooking oil at location s
UW_s	Upper bound of capacity of collection and preprocessing center of waste cooking oil at location s
LB_j	Lower bound dedicated on capacity of bio-refinery center at location j
UB_j	Upper bound of capacity of bio-refinery center at location j
LS_k	Lower bound dedicated on capacity of distribution center at location k
US_k	Upper bound of capacity of distribution center at location k
λ_{ft}	Amount of Jatropha yields per hectare at location f in period t

α	Conversion factor of Jatropha yields to Jatropha oil
β	Conversion factor of collected waste cooking oil to cleaned oil
γ	Conversion factor of Jatropha oil to biodiesel
ω	Conversion factor of cleaned waste cooking oil to biodiesel
φ	Discount factor
FCJ_f	Fixed cost of Jatropha cultivation at location f
FCC_i	Fixed cost of opening collection and preprocessing center of Jatropha yields at location i
FCW_s	Fixed cost of opening collection and preprocessing center of waste cooking oil at location s
FCB_j^r	Fixed cost of opening bio-refinery center at location j with technology r
FCS_k	Fixed cost of opening distribution center at location k
VCJ_f	Variable cost of Jatropha cultivation per hectare at location f
VCC_{it}	Variable cost per unit capacity installation for collection and preprocessing center of Jatropha yields at location i in period t
VCW_{st}	Variable cost per unit capacity installation for collection and preprocessing center of waste cooking oil at location s in period t
VCB_{jt}^r	Variable cost per unit capacity installation for bio-refinery center j with technology r in period t
VCS_{kt}	Variable cost per unit capacity installation for distribution center at location k in period t
PCJ_{ft}	Unit production cost of Jatropha yields at location f in period t
PCB_{jt}	Unit production cost of biodiesel at bio-refinery center j in period t
PCG_{jt}	Unit production cost of glycerin at bio-refinery center j in period t
PCO_{it}	Unit oil extraction cost from Jatropha yields in collection and preprocessing center i in period t
PCW_{st}	Unit cleaning cost of waste cooking oil at location s in period t
PCC_{gt}	Unit collection cost of waste cooking oil at supply center g in period t
ICJ_{it}	Unit inventory holding cost of Jatropha yields at collection and preprocessing center i in period t
ICW_{st}	Unit inventory holding cost of waste cooking oil at collection and preprocessing center s in period t
ICB_{jt}	Unit inventory holding cost of biodiesel at bio-refinery center j in period t
ICG_{jt}	Unit inventory holding cost of glycerin at bio-refinery center j in period t
ICS_{kt}	Unit inventory holding cost of biodiesel at distribution center k in period t
JCT_{flit}	Transportation cost of Jatropha yields from cultivation center f to collection and preprocessing center i by mode l in period t

WCT_{glst}	Transportation cost of waste cooking oil from supply center g to collection and preprocessing center s by mode l in period t
OCT_{iljt}	Transportation cost of Jatropha oil from collection and preprocessing center i to bio-refinery j by mode l in period t
VCT_{sljt}	Transportation cost of cleaned waste cooking oil from collection and preprocessing center s to bio-refinery j by mode l in period t
BCT_{jlkt}	Transportation cost of biodiesel from bio-refinery j to distribution center k by mode l in period t
GCT_{jlnt}	Transportation cost of glycerin from bio-refinery j to customer center n by mode l in period t
MCT_{klmt}	Transportation cost of biodiesel from distribution center k to customer center m by mode l in period t

Binary decision variables

x_f	1 if location f is selected for Jatropha cultivation; 0 otherwise
y_s	1 if location s is selected for opening collection and preprocessing center of waste cooking oil; 0 otherwise
u_i	1 if location i is selected for opening collection and preprocessing center of Jatropha yields; 0 otherwise
v_j^r	1 if bio-refinery j with technology r is opened; 0 otherwise
w_k	1 if location k is selected for opening distribution center of biodiesel; 0 otherwise

Continuous decision variables

IJ_{it}	Inventory level of Jatropha yields at collection and preprocessing center i in period t
IW_{st}	Inventory level of waste cooking oil at collection and preprocessing center s in period t
IB_{jt}^r	Inventory level of biodiesel at bio-refinery j in period t
IG_{jt}^r	Inventory level of glycerin at bio-refinery j in period t
IS_{kt}	Inventory level of biodiesel at distribution center k in period t
PJ_{ft}	Produced amount of Jatropha at cultivation center f in period t
PB_{jt}^r	Produced amount of biodiesel at bio-refinery j in period t
PG_{jt}^r	Produced amount of glycerin at bio-refinery j in period t
PO_{it}	Produced amount of Jatropha oil at collection and preprocessing center i in period t
PW_{st}	Produced amount of cleaned waste cooking oil at collection and preprocessing center s in period t
JT_{flit}	Transported amount of Jatropha yields from cultivation center f to collection and preprocessing center i by mode l in period t

WT_{glst}	Transported amount of waste cooking oil from supply center g to collection and preprocessing center s by mode l in period t
OT_{iljt}^r	Transported amount of Jatropha oil from collection and preprocessing center i to bio-refinery j with technology r by mode l in period t
VT_{sljt}^r	Transported amount of cleaned waste cooking oil from collection and preprocessing center s to bio-refinery j with technology r by mode l in period t
BT_{jlkt}^r	Transported amount of biodiesel from bio-refinery j with technology r to distribution center k by mode l in period t
GT_{jlnt}^r	Transported amount of glycerin from bio-refinery j to customer center n by mode l in period t
MT_{klmt}	Transported amount of biodiesel from distribution center k to customer center m by mode l in period t
CJ_f	Amount of cultivated area of Jatropha at location f (ha)
CC_{it}	Required capacity of collection and preprocessing center i of Jatropha seeds in period t
CEC_{it}	Amount of capacity expansion at collection and preprocessing center i of Jatropha seeds in period t
CW_{st}	Required capacity of collection and preprocessing center s of waste cooking oil in period t
CEW_{st}	Amount of capacity expansion at collection and preprocessing center s of waste cooking oil in period t
CB_{jt}^r	Required capacity of bio-refinery j with technology r in period t
CEB_{jt}^r	Amount of capacity expansion at bio-refinery j with technology r in period t
CS_{kt}	Required capacity of distribution center k in period t
CES_{kt}	Amount of capacity expansion at distribution center k in period t

In terms of the above notation, the proposed biodiesel SC network design model can be formulated as follows.

Objective function

Objective function of the proposed model minimizes total costs including:

Fixed opening costs: these costs include fixed cultivation costs of Jatropha, and opening costs of collection and preprocessing costs, bio-refineries, and distribution centers, respectively.

$$\sum_f FCJ_f x_f + \sum_i FCC_i u_i + \sum_s FCW_s y_s + \sum_j FCB_j^r v_j^r + \sum_k FCS_k w_k \quad (1)$$

Variable opening costs: these costs comprise variable Jatropha cultivation costs and capacity installation costs of collection and preprocessing costs, bio-refineries, and distribution centers, respectively.

$$\sum_f VCJ_f CJ_f + \sum_i \sum_t VCC_{it} CC_{it} + \sum_s \sum_t VCW_{st} CW_{st} + \sum_j \sum_t VCB_{jt}^r CB_{jt}^r + \sum_k \sum_t VCS_{kt} CS_{kt} \quad (2)$$

Production costs: these costs calculate total production costs of Jatropha seeds, collection costs of waste cooking oil, preprocessing costs of Jatropha seeds, filtering and cleaning costs of waste cooking oil, biodiesel production costs, and glycerin production costs, respectively.

$$\begin{aligned} & \sum_f \sum_t PCJ_{ft} PJ_{ft} + \sum_g \sum_t PCC_{gt} WO_{gt} + \sum_i \sum_t PCO_{it} PO_{it} + \sum_s \sum_t PCW_{st} PW_{st} \\ & + \sum_j \sum_t PCB_{jt} PB_{jt} + \sum_j \sum_t PCG_{jt} PG_{jt} \end{aligned} \quad (3)$$

Inventory holding costs: these costs consider inventory holding costs at collection and preprocessing centers of Jatropha seeds and waste cooking oil, bio-refineries, and distribution centers, respectively.

$$\sum_i \sum_t ICJ_{it} IJ_{it} + \sum_s \sum_t ICW_{st} IW_{st} + \sum_j \sum_t ICB_{jt} IB_{jt} + \sum_j \sum_t ICG_{jt} IG_{jt} + \sum_k \sum_t ICS_{kt} IS_{kt} \quad (4)$$

Transportation costs: this term takes into account different material transportation costs between the echelons of the network with different transportation modes in different periods, respectively.

$$\begin{aligned} & \sum_f \sum_l \sum_i \sum_t JCT_{flit} JT_{flit} + \sum_g \sum_l \sum_s \sum_t WCT_{glst} WT_{glst} + \sum_i \sum_l \sum_j \sum_r \sum_t OCT_{iljt} OT_{iljt}^r \\ & + \sum_s \sum_l \sum_j \sum_r \sum_t VCT_{sljt} VT_{sljt}^r + \sum_j \sum_r \sum_l \sum_k \sum_t BCT_{jlkt} BT_{jlkt}^r \\ & + \sum_k \sum_l \sum_m \sum_t MCT_{klmt} MT_{klmt} + \sum_j \sum_r \sum_l \sum_n \sum_t GCT_{jlnt} GT_{jlnt}^r \end{aligned} \quad (5)$$

Objective function term is achieved through summation of equations (1) to (5). NPV of the objective function is achieved through multiplying the abovementioned objective function value

by $\frac{1}{(1+\varphi)^{t-1}}$. The following constraints assure feasibility of the model for the considered assumptions.

Demand and supply satisfaction constraints

Constraints (6) and (7) satisfy biodiesel and glycerin demands at different cities for each period, respectively. In other words, the amount of biodiesel moved from distribution centers to a customer zone and also the amount of glycerin shipped from bio-refineries to a city are equal to corresponding demands in each period. Equations (8) and (9) ensure that all *Jatropha* seeds and waste cooking oil are collected and transported to related collection centers in each period.

$$\sum_k \sum_l MT_{kmt} = D_{mt} \quad \forall m, t \quad (6)$$

$$\sum_j \sum_r \sum_l GT_{jlt}^r = DE_{nt} \quad \forall n, t \quad (7)$$

$$\sum_l \sum_i JT_{flt} = PJ_{ft} \quad \forall f, t \quad (8)$$

$$\sum_l \sum_s WT_{glt} = WO_{gt} \quad \forall g, t \quad (9)$$

Production balance equations

Equation (10) calculates the amount of *Jatropha* yields in each cultivated area. Equations (11) and (12) calculate the amount of produced *Jatropha* oil and cleaned waste cooking oil at related collection and preprocessing centers in each period. Equation (13) states the amount of biodiesel produced at a bio-refinery with related technology in each period from *Jatropha* oil and waste cooking oil received from collection centers. Equation (14) states the amount of glycerin produced at a bio-refinery with related technology. Biodiesel and glycerin are produced according to the following transesterification process in bio-refineries (Fukuda et al., 2001).

Methanol is commonly used in transesterification process due to its low cost (Zhang et al., 2003).

$$PJ_{ft} = \lambda_{ft} CJ_f \quad \forall f, t \quad (10)$$

$$PO_{it} = \alpha \sum_f \sum_l JT_{flit} \quad \forall i, t \quad (11)$$

$$PW_{st} = \beta \sum_g \sum_l WT_{glst} \quad \forall s, t \quad (12)$$

$$PB_{jt}^r = \gamma \sum_i \sum_l OT_{rljt}^r + \omega \sum_s \sum_l VT_{sljt}^r \quad \forall j, r, t \quad (13)$$

$$PG_{jt}^r = (1 - \gamma) \sum_i \sum_l OT_{iljt}^r + (1 - \omega) \sum_s \sum_l VT_{sljt}^r \quad \forall j, r, t \quad (14)$$

Inventory balance equations

Equation (15) is inventory balance constraint at a collection and preprocessing center of Jatropha seeds. This constraint ensures that the inventory of Jatropha seeds at collection and preprocessing center in any period is equal to summation of inventory of Jatropha seeds left from previous period, the amount of Jatropha seeds produced in that period minus the amount of Jatropha seeds transformed to oil and shipped to bio-refineries. Equation (16) states that inventory of collected waste cooking oil at any collection and preprocessing center is summation of the inventory left from previous period, collected waste cooking oil in that period minus the cleaned waste cooking oil shipped to bio-refineries. Constraints (17) and (18) are inventory balances for biodiesel and glycerin at a specific bio-refinery, respectively. Equation (19) considers biodiesel inventory balance in a specific distribution center in each period.

$$IJ_{it} = IJ_{i,t-1} + \sum_f \sum_l JT_{flit} - \left(\frac{1}{\alpha}\right) \sum_l \sum_j \sum_r OT_{iljt}^r \quad \forall i, t \quad (15)$$

$$IW_{st} = IW_{s,t-1} + \sum_g \sum_l WT_{glst} - \left(\frac{1}{\beta}\right) \sum_l \sum_j \sum_r VT_{sljt}^r \quad \forall s, t \quad (16)$$

$$IB_{jt}^r = IB_{j,t-1}^r + PB_{jt}^r - \sum_l \sum_k BT_{jlkt}^r \quad \forall j, r, t \quad (17)$$

$$IG_{jt}^r = IG_{j,t-1}^r + PG_{jt}^r - \sum_l \sum_r \sum_n GT_{jlnt}^r \quad \forall j, r, t \quad (18)$$

$$IS_{kt} = IS_{k,t-1} + \sum_j \sum_r \sum_l BT_{jlkt}^r - \sum_l \sum_m MT_{klmt} \quad \forall k, t \quad (19)$$

Capacity expansion constraints

Constraint (20) binds lower and upper bounds of determined locations for Jatropha cultivation. Lower bound is considered due to economy of scale consideration and upper bound is considered because of biodiversity concerns. Regarding the fact that Jatropha plants yield after two years of cultivation and in order to keep continuous yielding, we assume that capacity of Jatropha cultivation area is not dependent on time period. On the other hand, capacity of other facilities is dependent on time periods to be expanded over coming time periods. In this respect, constraints (21) and (22) take into account capacity expansion and lower and upper bounds for established collection and preprocessing centers of Jatropha seeds. Capacity of any established facility in each period is equal to capacity determined in prior period and capacity expanded in current period. Constraints (23) and (24) are capacity expansions and lower and upper bounds in collection and preprocessing centers of waste cooking oil. Constraints (25) and (26) are capacity expansions and lower and upper bounds for bio-refineries with related technology. Constraint (27) implies that at most one technology alternative can be installed in a specified location for opening bio-refinery. Constraints (28) and (29) are capacity expansions and lower and upper bounds in distribution centers. Note that when a facility is determined (i.e., corresponding binary variable is 1), its corresponding capacity will be between defined lower and upper bounds. On the other hand, when binary variable of a specific facility is zero, its related capacity will be zero.

$$x_f LA_f \leq CJ_f \leq x_f UA_f \quad \forall f \quad (20)$$

$$CC_{it} = CC_{i,t-1} + CEC_{it} \quad \forall i, t \quad (21)$$

$$u_i LC_i \leq CC_{it} \leq u_i UC_i \quad \forall i, t \quad (22)$$

$$CW_{st} = CW_{s,t-1} + CEW_{st} \quad \forall s, t \quad (23)$$

$$y_s LW_s \leq CW_{st} \leq y_s UW_s \quad \forall s, t \quad (24)$$

$$CB_{jt}^r = CB_{j,t-1}^r + CEB_{jt}^r \quad \forall j, r, t \quad (25)$$

$$v_j^r LB_j \leq CB_{jt}^r \leq v_j^r UB_j \quad \forall j, r, t \quad (26)$$

$$\sum_r v_j^r \leq 1 \quad \forall j \quad (27)$$

$$CS_{kt} = CS_{k,t-1} + CES_{kt} \quad \forall k, t \quad (28)$$

$$w_k LS_k \leq CS_{kt} \leq w_k US_k \quad \forall k, t \quad (29)$$

Production and inventory capacity constraints

Constraints (30) to (33) are capacity constraints of established collection and preprocessing centers of Jatropha seeds, collection and preprocessing centers of waste cooking oil, bio-refineries, and distribution centers, respectively. In other words, the amount of materials handled in a specific facility don't exceed its corresponding capacity, which is taken into account via continuous variable. Constraints (34) to (37) are capacity limitations for inventory holding at established facilities.

$$\sum_f \sum_l JT_{flit} \leq CC_{it} \quad \forall i, t \quad (30)$$

$$\sum_i \sum_l OT_{iljt} + \sum_s \sum_l VT_{sljt} \leq CB_{jt} \quad \forall j, t \quad (31)$$

$$\sum_g \sum_l WT_{glst} \leq CW_{st} \quad \forall s, t \quad (32)$$

$$\sum_j \sum_l BT_{jlkt} \leq CS_{kt} \quad \forall k, t \quad (33)$$

$$IJ_{it} \leq CC_{it} \quad \forall i, t \quad (34)$$

$$IB_{jt} \leq CB_{jt} \quad \forall j, t \quad (35)$$

$$IW_{st} \leq CW_{st} \quad \forall s, t \quad (36)$$

$$IS_{kt} \leq CS_{kt} \quad \forall k, t \quad (37)$$

Finally, constraints (38) and (39) enforce binary and non-negativity restrictions on the related decision variables.

$$x_f, y_s, u_i, v_j^r, w_k \in \{0, 1\} \quad \forall f, s, i, j, r, k \quad (38)$$

$$\text{All Continuous decision variables} \geq 0 \quad (39)$$

4. Real case implementation and evaluation

In this section, to test the usefulness and efficiency of the proposed biodiesel supply chain network design model is implemented in a real case in Iran.

4. 1. Biofuel extension and potential feedstocks in Iran

Iran is one of the middle-east countries being rich sources of fossil fuels and one of the biggest exporters of crude oil in the world. Air quality problems of the Iran's big cities because of emissions exhausted from transportation sector have made some serious problems including respiratory and skin diseases, acid rains, and lack of good living condition in these cities. These problems, in turn, have negative impacts on sustainable development dimensions including social, environmental, and economic aspects. In order to decrease burdens of the mentioned problems, Iran's government is eliminating subsidies from domestic fossil fuels consumptions and granting biofuels and other renewable energy usages to move toward sustainable development. Energy consumption evaluation in Iran shows a great increasing trend in renewable energy consumption (Azadeh et al., 2013). Biofuel utilization in Iran goes back to recent decade. Bioethanol extensional programs have been started since 2001, but biodiesel extensional programs have been issued since 2009. In this respect, Iran is planning to extend

1 current limited capacity to substitute about 20% of fossil diesel consumption by biodiesel (i.e.,
2 B20). This paper is an attempt to design biodiesel supply chain network in Iran to substitute the
3 predetermined percentage of diesel by biodiesel in subsequent years.

4 Iran has a great potential for exploiting different biomass resources and energy crops such
5 as sunflower, sorghum, sugar beet, switchgrass, and Jatropha. Indeed, there are good climate
6 condition and waste lands in Iran actuating investors and farmers in agriculture activities. In
7 addition, Iran has extensive hectares of arid and semi-arid areas that could be exploited for
8 cultivation of energy crops such as Jatropha that grows in marginal lands, efficiently. According
9 to Jatropha belt ($30^{\circ} N, 35^{\circ} S$), which shows the most suitable areas for Jatropha cultivation in the
10 worldwide, southern half of Iran is the most appropriate area for Jatropha cultivation.

11 Considering the fact that Iran imports about 80 percent of its edible oil consumption,
12 utilizing sources of edible oils such as palm, corn, sunflower, soya, and cotton for biodiesel
13 production is irrational and would be a menace for food supply resources. Therefore, exploiting
14 other non-edible oil sources such as Jatropha can be a great opportunity for Iran. Jatropha
15 cultivation planning in Iran is performed for preventing soil erosion, reducing the desert, and
16 biodiesel production. Another interesting source of biodiesel production in Iran is utilizing waste
17 cooking oil, which is produced about 300,000 tons, annually.

18 Currently, there is one bio-refinery producing biodiesel with mediocre capacity in Iran.
19 The feedstock required for biodiesel production at this bio-refinery is acquired from edible oil
20 crops and animal fats. Due to the emerged challenges in biodiesel production from edible
21 oleaginous sources, Iran's government is aimed to utilize non-edible sources of feedstock for
22 biodiesel production. Considering the weather condition and oil consumption in Iran, Jatropha
23 and waste cooking oil are the most promising feedstock for biodiesel production in Iran.

1 Although Iran is one of the biggest exporters of crude oil in the world, it imports considerable
2 amount of its need for diesel and gasoline with high quality from European countries to reduce
3 the toxic emissions of fossil fuels combustion. Therefore, any attempt for domestic production of
4 green fuels such as biodiesel is highly supported and granted.

4.2. Data gathering and estimation

To estimate the economic and technical parameters used in the proposed model, reliable historical data and scientific reports are used. To estimate biodiesel demands for 40 periods, first fossil demands are predicted for 40 periods according to historical data. Then, the predetermined percentages of fossil diesel in different periods are considered as biodiesel demands. Figure 2 shows the estimated biodiesel demand for 25 considered customer centers. In this figure, each color is representative of a specific city. Biodiesel demand in big cities (i.e., Tabriz, Isfahan, Khorasan R., Khozestan, Fars) and capital (i.e., Tehran) starts with B2 type and reaches B15 (85% diesel and 15% biodiesel) and B20 after planning horizon, respectively. Other cities are expected to reach B5 after planning horizon. This policy is taken into account to reduce the high amount of greenhouse gases emitted due to fossil fuel combustion in big cities. Since it is not reasonable to spend high transportation costs to fulfill very low biodiesel demands, 5 cities with very low demand of biodiesel are not considered as customer centers. Therefore, there would be 25 cities demanding biodiesel. Note that biodiesel demand incremental trend is taken place annually not periodically. For example, predicted biodiesel demand for summer in 2015 is higher than that of 2014, but may be lower than biodiesel demand for spring in 2015.

Fig. 2. Biodiesel estimated demand for different cities

Glycerin as a by-product of transesterification process is used in producing hygienic products. 11 cities of Iran have factories producing hygienic products. About 75% of hygienic products are produced in Tehran. We assume that demand of glycerin in each city is consistent with the capacity of hygienic factory in that city. That is, the estimated produced glycerin is divided between 11 cities according to their capacity for producing hygienic products.

The amount of waste cooking oil produced in each city is provided from Iranian Fuel Conversion Company (<http://ifco.ir>). Fixed opening costs, variable opening costs, production and inventory holding costs are taken into account according to own calculation. Transportation cost between each two cities is calculated through multiplying unitary transportation cost, which is extracted from An et al. (2011b), by distance between them. Ministry of Roads & Urban Development (<http://mrud.ir>) is responsible for the data describing road distance among cities. Also, Asia Seir Aras Company (<http://asiaseiraras.com>) is responsible for the gathered data describing rail distance between cities. Conversion factor parameters are achieved from scientific reports according to Table 5. It should be noted that the parameters reported in Table 5 are

average values found in literature and one may find some difference in the reported values in the literature. Discount factor is assumed to be 16% per year. It should be noted that road mode is possible among all 30 considered cities, but rail mode is possible only among 11 cities.

Table 5. Conversion factors estimation

Conversion factor	Value	Source
α	0.35	Achten et al. (2007); Brittain and Litaladio (2010)
β	0.95	Assumption
γ, ω	0.83	Achten et al. (2007); Zhang et al., 2003; Fukuda et al. (2001)

Conversion factor of Jatropha cultivated area to Jatropha seeds (λ_{jt}) is location and time period dependent. Locations with good ecologic and soil condition have higher amount of conversion. It is worthy to note that Jatropha yields is altered from 2 to 12 t/ha/y in the literature according to ecological and soil condition (Openshaw, 2000; Jongschaap et al., 2007). Since arid and semi-arid areas are considered as potential areas for Jatropha cultivation in the studied case, we assume the Jatropha yields are between 2 to 7 t/ha/y. In mild condition like as our case, this amount of Jatropha yields is expected according to real experiences and scientific reports (Achten et al., 2008; Van Eijck et al., 2014). It is worthy to note that these yields are in terms of seeds instead of the whole fruit. In other words, the whole fruit yield per hectare, per year, will range from about 0.9 to 26 t (Openshaw, 2000). We consider $3 \times 3 \text{ m}^2$ space for cultivation each Jatropha plant and so there would be about 1100 plants per hectare (Heller, 1996). Due to space limitation, the used data are not presented here.

4.3. Results and discussion

The resulted biodiesel supply chain network in our case has 23 candidate locations for Jatropha cultivation, 30 specified locations for waste cooking oil supply centers, 30 candidate

locations for collection and preprocessing centers of Jatropha yields, 30 candidate locations for collection and preprocessing centers of waste cooking oil, 30 candidate locations for bio-refineries, 30 candidate locations for distribution centers, 11 specified locations for glycerin demand centers, 25 specified locations for biodiesel demand centers, 2 transportation modes, and 10 years (40 periods) planning horizon. Therefore, the size of the considered network is equal $23 \times 30 \times 30 \times 30 \times 30 \times 30 \times 11 \times 25 \times 2 \times 40$ which is a large supply chain network in which the optimum number and capacity of facilities, transportation mode, inventory amount, production amount, and material flows in different periods should be determined.

Due to MILP structure of the proposed model, CPLEX solver of the GAMS[®] optimization software is used for solving the model. The optimum solution was achieved after 1659 seconds. The presented model has 50166 equations, 701924 continuous variables, 173 binary variables. Objective function value and its components according to Iran currency have been demonstrated in Table 6. All objective function's components have major share in total value of objective function. These components create clear insight for senior management to fund different required costs. For example, transportation costs could be compared respect to costs incurred by third party logistics and then related decisions about outsourcing could be made.

Table 6. Objective function value and its components (MIRR)

Objective function value	Fixed opening costs	Variable opening costs	Production costs	Inventory holding costs	Transportation costs
6.5990E+9	1.1477E+6	5.8010E+8	7.4577E+6	4.5292E+5	1.9949E+6

MIRR: Million Iranian Rials

According to acquired results in transportation section of the constructed biodiesel SC network, about 78 percent of material transportation between different echelons of the network is performed by road way and 22 percent of total material transportation is done by rail way. This could be explained due to low rail connections among cities.

Two cities namely *Sistan va Balochestan* with 1000000 (ha) and *Hormozgan* with 61344 (ha) are selected among 23 candidate locations for *Jatropha* cultivation. The best locations for collection and preprocessing centers of *Jatropha* seeds and waste cooking oil with the amount of corresponding required capacities have been illustrated in Figures 3 and 4, respectively. It should be noted that according to the structure of the proposed model, the needed capacity for established facilities is determined periodically, but due to space limitations we have presented the installed capacities in terms of year. Figure 3 shows stepwise increasing installed capacities for collection and preprocessing centers of *Jatropha* seeds. This is because that *Jatropha* yields are significantly improved over years before maturity. Figure 4 demonstrates smooth increasing installed capacities for collection and preprocessing centers of waste cooking oil. This behavior is because that amount of waste cooking oil supplied by different cities in different periods is smoothly increased.

Fig. 3. The best locations and installed capacities for established collection and preprocessing centers of *Jatropha* seeds

Fig. 4. The best locations and installed capacities for established collection and preprocessing centers of waste cooking oil

Figure 5 illustrates the best locations specified for establishing bio-refineries with corresponding capacities to be installed over the years. Note that there is one active bio-refinery in *Isfahan* with second type of technology. This bio-refinery don't expand its capacity over planning horizon. Moreover, second type of technology (i.e., cold fusion reactor) is selected for installation in all determined bio-refineries.

Fig. 5. The best locations and installed capacities for bio-refineries

Figure 6 shows the best locations determined for constructing biodiesel distribution centers and related capacities to be installed over the coming years. It can be seen from Figure 6 that up to the fourth year only *Khorasan J.* city is enough for biodiesel distribution.

Fig. 6. The best locations and installed capacities for biodiesel distribution centers

Figures 3 to 6 show the efficiency and usefulness of the proposed model in designing biodiesel SC network. It is worthy to note that most of presented models in the literature (Chen and Fan, 2012; Kim et al., 2011a) consider static condition for designing biofuel supply chain network due to simplicity of solving procedure. However, as illustrated in Figures 3 to 6, considering the biodiesel supply chain network design problem under dynamic condition will avoid opening facilities in unnecessary periods which in turn save remarkable investment costs.

5. Conclusion

Finding sustainable and viable solution to problems such as food crisis, energy security, environmental, and poverty reduction, researchers and development practitioners have introduced second-generation biofuel production from non-edible feedstocks as one of the promising solutions. Designing biofuel supply chain network in an integrated way significantly

1 impacts on commercial viability of biofuels. In this paper, firstly we review and systematically
2 categorized the recent works presented for designing biofuel supply chain network. Then,
3 motivated from the gaps in the literature, an integrated biodiesel supply chain network design
4 model is developed under dynamic condition. The proposed model is a multi-period and MILP
5 model which integrates the most important strategic and tactical level decisions to avoid sub-
6 optimal solutions. The decisions to be addressed by the proposed model include determining the
7 numbers, locations, and capacities of facilities in different echelons, suitable transportation
8 modes, suitable technology in bio-refineries, material flow within the network, and optimal
9 production planning. We consider Jatropha seeds and waste cooking oil as non-edible feedstocks
10 for second-generation biodiesel production.

11 In order to investigate the performance of the proposed model, a real case in Iran is
12 implemented. The results show that considering the biodiesel supply chain network design model
13 under dynamic condition will avoid unnecessary establishing costs. Also, considering all related
14 echelons from feedstock supply centers to customer zones in biodiesel supply chain optimization
15 will avoid sub-optimal solutions. Some future research directions can be visualized according to
16 the investigated literature gaps and the results of this paper as follows.

17 The future models should move from first-generation biofuels SC optimization towards
18 second-generation biofuel SC optimization. In this respect, all related echelons from feedstock
19 supply centers to end customer zones should be considered in optimization. In addition, all
20 important tactical and strategic decisions should be taken into account under dynamic condition
21 to be determined in an optimum way. Although the above considerations will lead to large-scale
22 supply chains, the resulted models would be so compatible with real world assumptions.
23 Developing efficient heuristic and exact solution algorithms is an essential need in this area. Our

review doesn't show any comprehensive solution algorithm developed for solving the biofuel supply chain models in large scales and most of them use commercial optimization softwares. Another important issue is addressing uncertainty in biofuel supply chain model. Feedstock yields, biofuel demands, different costs, and technical parameters are the most common parameters being subject to uncertainty. Sustainability issues i.e. environmental and social aspects should be addressed besides economic aspect. This consideration will lead to multi-objective biofuel supply chains optimization models.

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Figures:

Fig. 1. The structure of the considered biodiesel SC network

Fig. 2. Biodiesel estimated demand for different cities

Fig. 3. The best locations and installed capacities for established collection and preprocessing centers of Jatropha seeds

Fig. 4. The best locations and installed capacities for established collection and preprocessing centers of waste cooking oil

Fig. 5. The best locations and installed capacities for bio-refineries

Fig. 6. The best locations and installed capacities for biodiesel distribution centers

Tables:

Table 1. Classification codes of the Biofuel supply chain networks

Planning Horizon	Code	Output decisions	Code
Long-term (Strategic)	Str	Location/allocation	L
Mid-term (Tactical)	Ta	Capacity of facilities	CF
Network layers		Number of facilities	NF
<i>Forward layers</i>		Flow amount	FA
Supplier centers	SC	Inventory	I
Collection centers	CC	Transportation mode	TM
Production centers	PC	Type of Technology	T
Distribution centers	DI	Number of vehicles	NV
Customers	CU	Objectives	
Problem properties		<i>Economic objectives</i>	
<i>Facility capacity</i>		Min cost/Max profit	C
Capacitated	Ca	Max responsiveness	R
Uncapacitated	UC	Max demand satisfaction	S
<i>Products</i>		Risk minimization	RI
Single-product	SP	<i>Environmental objectives</i>	
Multi-product	MP	Min environment impact	EI
<i>Periods</i>		Max resource conservation	RC
Single-period	SPr	<i>Social objectives</i>	
Multi-period	MPr	Max employment opportunity	E
Uncertainty		Max local development	LD
Supply uncertainty	US	Min Product risk	PR
Process uncertainty	UP	Min work hazard	W
Demand uncertainty	UD		

Table 2. Properties of the biofuel supply chain networks

Article	Horizon	Layers	Properties	Uncertainty	Output	Objectives
Cundiff et al. (1997)	Ta	SC, CC, PC	Ca, MPr	US	CF, FA	C
Tan et al. (2009)	Ta	SC, PC	Ca, MP, MPr	US, UD	FA	EI
Čuček et al. (2010)	Str, Ta	SC, PC	Ca, MP	-	L, NF, FA, T	C, EI
Huang et al. (2010)	Str, Ta	SC, PC, CU	Ca, MP, MPr	-	L, NF, CF, FA	C
An et al. (2011b)	Str, Ta	SC, CC, PC, DI	Ca, MP, MPr	-	L, T, CF, FA	C
Papapostolou et al. (2011)	Str, Ta	SC, PC	Ca, MP, SPr	-	FA	C
Kim et al. (2011a)	Str, Ta	SC, PC, CU	Ca, MP, SPr	US, UP, UD	L, NF, FA, T, CF	C
Kim et al. (2011b)	Str, Ta	SC, PC, CU	Ca, MP, SPr	-	L, NF, FA, T, CF	C
Dal-Mas et al. (2011)	Str, Ta	SC, PC, CU	Ca,MP,MPr	US, UD	L, NF, FA, CF, NV, TM	C
Giarola et al. (2011)	Str, Ta	SC, PC, CU	Ca, MP, MPr	-	L, NF, FA, T, CF, TM	C, EI

Leão et al. (2011)	Str, Ta	SC, CC, PC	Ca, SP, MPr	-	L, NF, FA, T, CF	C
Andersen et al. (2012)	Str, Ta	SC, PC, DI,	Ca, MP, MPr	-	L, NF, CF, FA, I, NV	C
Judd et al., (2012)	Str, Ta	SC, CC	Ca, SP, SPr	-	L, I, FA, NV	C
Chen and Fan (2012)	Str, Ta	SC, PC, DI, CU	Ca, MP, SPr	US, UD	L, NF, FA, CF	C
Ng et al. (2013)	Str, Ta	SC, PC,	Ca, MP	-	L, CF, FA	C
Ebadian et al. (2013)	Str, Ta	SC, CC, PC	MP, MPr	US	L, I, FA	C
Osmani and Zhang (2013)	Str, Ta	SC, PC, CU	Ca, MP, SPr	US, UD	L, CF, FA	C
Srinivasan and Malliga (2013)	Str	CC	SP, SPr	-	L	C
Santibañez-Aguilar et al. (2014)	Str, Ta	SC, PC, DI, CU	Ca, MP, MPr	-	CF, L, NF, FA, TM, NV, T	C, EI, E
Our work	Str, Ta	SC, CC, PC, DI, CU	Ca, MP, MPr	-	L, NF, FA, CF, NV, TM, T	C

Table 3. Codes of modeling type

Modeling	Code
Linear programming	LP
Integer Programming	IP
Mixed integer linear programming	MILP
Mixed integer non-linear programming	MINLP
Mixed integer goal programming	MIGP
Scenario based stochastic mixed integer programming	SSMIP
Fuzzy programming	FP
Scenario-based mixed integer robust optimization	SMIRO
Uncertainty set based mixed integer robust optimization	UMIRO

Table 4. Modeling type and solution method

Article	Modeling	Solution method	Case study-Country
Cundiff et al. (1997)	LP	Commercial solver	Biomass supply- Piedmont county, U. S.
Tan et al. (2009)	FP	Max-min fuzzy solution	Hybrid bioethanol and biodiesel-Philippine
Čuček et al. (2010)	MILP	Commercial solver	Biomass supply- Central European
Huang et al. (2010)	MILP	Commercial solver	Biomass supply- California, U. S.
An et al. (2011b)	MILP	Commercial solver	Biomass supply- Central Texas, U. S.
Papapostolou et al. (2011)	LP	Commercial solver	First-generation biofuel- Greece
Kim et al. (2011a)	SMILP	Commercial solver - Mont carlo simulation and global	Bioethanol- U. S.

sensitivity analysis			
Kim et al. (2011b)	MILP	Commercial solver	Hybrid bioethanol and biodiesel- U. S.
Dal-Mas et al. (2011)	SMILP	Scenario-based stochastic programming	Ethanol- Italy
Giarola et al. (2011)	MILP	ϵ -constraint	Hybrid first and second-generation Bioethanol- Italy
Leão et al. (2011)	MILP	Commercial solver	Biodiesel-Brazil
Andersen et al. (2012)	MILP	Commercial solver	Biodiesel- Argentina
Judd et al., (2012)	MILP	Two stage decomposition	Cellulosic ethanol- Central Virginia, U. S.
Chen and Fan (2012)	SMILP	Progressive hedging (PH) method based on Augmented Lagrangian	Ethanol- California, U. S.
Ng et al. (2013)	MINLP	Commercial solver	Biodiesel- Malaysia
Ebadian et al. (2013)	MILP	Commercial solver - simulation	Cellulosic ethanol- Canada
Osmani and Zhang (2013)	SMILP	Discretizing continuous probability to scenarios and solving with Commercial solver	Ligno-cellulosic ethanol- U. S.
Srinivasan and Malliga (2013)	IP	Myopic and exchange heuristics	Jatropha warehouse location- India
Santibañez-Aguilar et al. (2014)	MILP	ϵ -constraint	Biofuel- Mexico
Our work	MILP	Commercial solver	Biodiesel-Iran

Table 5. Conversion factors estimation

Conversion factor	Value	Source
α	0.35	Achten et al. (2007) ; Brittaine and Lutaladio (2010)
β	0.95	Assumption
γ, ω	0.83	Achten et al. (2007) ; Zhang et al., 2003 ; Fukuda et al. (2001)

Table 6. Objective function value and its components (MIRR)

Objective function value	Fixed opening costs	Variable opening costs	Production costs	Inventory holding costs	Transportation costs
6.5990E+9	1.1477E+6	5.8010E+8	7.4577E+6	4.5292E+5	1.9949E+6

MIRR: Million Iranian Rials