RAIRO-Oper. Res. 55 (2021) S2653–S2675
https://doi.org/10.1051/ro/2020104

RAIRO Operations Research
www.rairo-ro.org

A SUSTAINABLE CROSS-EFFICIENCY DEA MODEL FOR INTERNATIONAL MSW-TO-BIOFUEL SUPPLY CHAIN DESIGN

Mahsa Ghadami, Hadi Sahebi*, Mirsaman Pishvaee and Hani Gilani

Abstract. Fossil fuels, as the primary source of the energy supply in today's global society, are being depleted much faster than expected and are raising serious environmental and social concerns for contemporary societies. To deal with issues, a global movement towards the generation of sustainable renewable energy is underway. One of the most promising sources of renewable energy alternatives is the use of municipal solid waste, as a biomass source since it does not endanger food security and considerably the biomass made by municipal solid waste will enable the appropriate management of the waste and help cities to be sustainable. The supply chain of converting the municipal solid waste to bioenergy is a challenging issue that have attracted the attention of academic and industrial research. In this direction, a three-echelon mathematical model is developed to design MSW-to-biofuel supply chain network. This supply network is a global network; hence, the international supply chain-related issues and the disruption in the raw material supply have also been studied. Identifying appropriate potential locations to site facilities is a challenge faced in the municipal solid waste-to-biofuel supply chain models. To achieve goal, in this research, the use has been made of a proposed sustainable cross-efficiency DEA model which is an effective ranking method, especially for finding potential points. To deal with sustainability, the social and environmental indicators have also been presented in the form of some criteria in this DEA method. In addition, effort has been made to improve the ecological indicators of the supply chain design in line with the sustainable development as an objective function. Finally, in order to validate the proposed model, a case study with real data is presented.

Mathematics Subject Classification. 90C90, 90C29.

Received May 14, 2019. Accepted September 20, 2020.

1. Introduction

Nowadays, with the increased population and developed industry and technology, the human's need for fossil fuels has been so highly increasing that the global energy consumption experienced a sudden considerable rise in 1975 and showed an increase of about 5.6% in 2010 [31]. Fossil fuels' increased demands not only intensify the risk of their exhaustion, but their consumption-caused environmental pollutions also challenge governments and authorities. Therefore, the countries are trying to reduce their dependence on these nonrenewable fuels and

Keywords. Ecological indicators, sustainable biofuel systems, municipal solid waste management, international supply chain design, sustainable data envelopment analysis, disruption.

School of Industrial Engineering, Iran University of Science & Technology, Narmak, IR 16846-13114, Tehran.
*Corresponding author: hadi_sahebi@iustacir

are making efforts to increase the share of renewable and clean energies in their energy portfolio [13]. Shifting to renewable energy sources is a promising alternative to improve ecological indicators.

Biomass, as renewable energy, includes a wide range of biological-origin materials such as starch base (wheat, rice, etc.), sugar base (sugar beet, sugar cane, etc.), oil crop (soy, etc.), energy crops (switchgrass, Jatropha, sorghum, etc.), and organic wastes (forest waste, agricultural waste such as rice/wheat straw, sugar cane molasses, etc.) [15]. Initially, the first generation biomass (some materials used as food) was used to generate sustainable energy; during 2000–2011 the biofuel production from such materials as corn, sugar cane, and starch increased in the world by almost 13.8%, most of which was related to the US and Brazil [31]. Because of food security, after a while, the use of the first-generation biomass was banned, causing a considerable reduction of the production of biofuels from it [26]. The second generation biomass includes agricultural wastes like corn pods, Switchgrass, Miscanthus, and Jatropha which are largely found in the municipal waste. Another problem faced today is properly managing the municipal solid wastes, especially in such metropolitans as Tehran. If the municipal wastes are not managed appropriately, Methane (a greenhouse gas) will be emitted in the environment and will pollute the air; therefore, finding a way for appropriate waste management is on the agenda of many countries to enhance their ecological indicators. Cellulosic municipal waste is a type of second-generation biomass and generating energy from it is an excellent option for the authorities to sustainability manage the municipal waste [12].

Bioethanol is a clean fuel that can be produced from the cellulosic part of the municipal solid wastes. Thus, the production of bioethanol reduces the emission of greenhouse gases [24], produced by municipal solid wastes. As a clean fuel, it also contributes for the environmental aspect of sustainable development. Accordingly, bioethanol production from cellulosic municipal wastes to produce liquid biofuel for transportation will positively affect the environmental aspect of sustainable development. As a result, this research has focused on the supply chain (SC) of biofuels (bioethanol plus petrol) produced from municipal solid wastes.

To configure a supply chain, an initial set of potential points is usually defined for the construction of facilities, and then the best moments are selected using the mathematical modeling. The definition of the initial set of potential points of a supply chain is an important step which has to consider the eco-efficiency approach in the decision process. Therefore, the use of a multi-criteria approach is indicated in this case, allowing to also consider some ecological criteria in the initial step. Using this procedure, the problem solution space will get smaller and the complexities caused by a large problem space will be reduced. In this research, the multi-criteria approach used was the Data Envelopment Analysis (DEA), which is an important method that has attracted the attention of many researchers in the last few decades [33].

This study has presented some environmental factors related to sustainable development in the form of some indices of the new "Data Envelopment Analysis" model. Also developed model is to consider such ecological and social aspects in the form of the criteria of the new DEA model. The results of this model present the potential points in the network design supply chain. In other words, ranking the potential points are used to design a sustainable supply network of facilities by the effects. The next contribution is to propose a new network design global supply chain model based on customs regulations because it considered the model decision by the amount of raw material import and final product export as an important issue [29].

This model considers the different forms of disruption in each layer of the proposed supply chain. Disruption may affect the decision-making process by creating transportation risk and non-delivery of goods. The reasons for occurrence can be different for instance road breakdown, lack of raw material, or political issues. The present study implements political (sanctions) and transportation disruption by the scenario base model.

This paper has been so structured as to review the related literature in Section 2. The problem statement is presented in Section 3, and a mathematical programming model for the municipal solid waste-to-biofuel supply chain network (MSW2B-SCN) design is developed. Section 4, solution method, introduces the "Sustainable Data Envelopment Analysis" model as a technique to order set of potential points for production centers, and bi-objective programming model is also discussed. The case study is explained in Section 5, and Section 6 presents the numerical model results and sensitivity analysis. And, Section 7 provides the final conclusions and suggests promising avenues for further future studies.

2. Literature review

In this section, some papers related to biomass (especially bio-wastes and biofuels, including bioethanol) are reviewed for more acquaintance with the related literature. Then the existing gaps are discussed to better introduce the present study. Since biomass-related issues lie in the group of new research subjects that have received special attention in the past few decades, the mathematical models presented in this area address such strategic issues as the design of SC, selection of the type of biomass and final product, selection of technology, capacity of facilities, and so on. Next, we will introduce some papers that have addressed the SC design modeling of the biomass.

Marvin *et al.* [17] developed a MILP model to determine bio facility locations and capacities. The corn ethanol facilities are considered to produce biofuel by utilizing eight types of biomass. A detailed cash flow analysis is employed to select biomass processing technologies and facility sites. Sharma *et al.* [32] presented a multi-period, stochastic model for the SC design of different biomass types wherein they studied the climatic uncertainty in the biomass accessibility. Balaman *et al.* [4] presented the mathematical model for the SC design of extracting electricity from animal wastes. They also showed the reverse logistics and the return of the remaining waste in an anaerobic digester to agricultural lands as fertilizers and accordingly presented an integrated, revers and forward) mathematical model. Later in the same year, they added a second objective function with an environmental theme and used the fuzzy goal programming to solve their bi-objective model [5]. Marufuzzaman *et al.* [16] raised the issue of hubs in the biomass SC design, discussed the hub disruption occurrence in modeling, and used Benders decomposition to solve their model. Using scenario-based programming, Shabani *et al.* [30] consider uncertainty in the biomass SC and addressed, contrary to other models that focus most on the strategic level, to decision making at the tactical level (*e.g.*, planning and scheduling the production of electricity from biomass). Azadeh *et al.* [2] concentrated on the transportation network in the biomass SC and studied the disruptions of the communication paths between facilities. A differentiating point in their proposed model is the use of robust programming. By presenting a bi-objective model that minimized cost and maximized the accessibility of the communication routes, Poudel *et al.* [25] raised such issues as hubs, multi-modal transportation, and disruptions in communication routes and used Benders method to solve their model. In the mentioned papers, the focus has mostly been on other biomass resources, and the municipal waste, as a very attractive source of bioenergy production, has been neglected. In addition, most of these papers have been interested in producing electrical energy from the biomass. In the present paper, the municipal waste has been studied as a significant source in the biomass SC and focus has been on a mixture of bioethanol and petrol to produce a biofuel that can be in the road transportation.

To reduce our dependence on fossil fuels, the conversion of lignocellulosic biomass to fuels is an interesting method. Providing an effective biomass SC network is essential to meet bioethanol demand. In this direction, Ng and Maravelias [21] dealt with a mixed-integer non-linear program for biomass selection and allocation, technology selection, capacity planning and inventory controlling at depots. An *et al.* [1] proposed a mathematical model for the design of the l bioethanol supply chain from the lignocellulose biomass and study the transportation network-related decisions in their model by defining the network in the form of graphs and arcs. Corsano *et al.* [6] studied the bioethanol supply chain from sugarcane molasses and placed the main focus of their work on production planning and scheduling. Next, in 2014, they added the interior design of the factory layout to their model. Corsano *et al.* [7] and Xie *et al.* [35] proposed a model for the transportation network and supplying bioethanol from the cellulosic biomass; seasonal biomass resource was an innovation in their work. Although all the mentioned papers have been about bioethanol SC, none has specifically mentioned the cellulosic part of the municipal solid waste as a potential source of producing bioethanol, whereas using the solid cellulosic waste for the production of bioethanol has many advantages. Accordingly, the present research has focused on the municipal solid wastes-to-bioethanol supply chain management.

Doggar *et al.* [8] studied the biomass power generation potential and utilization in Pakistan. The presented that 38 000 GWh electricity can be generated using crop residue and animal waste, annually, in Pakistan. There is no research, to our knowledge, to study the potential of biomass energy from municipal solid waste in Iran. As a clear result, this paper focuses on biofuel supply chain design from municipal solid waste in Iran.

A review of the related literature showed that there are a few papers that have addressed the technical, economic, and environmental analyses of extracting bioethanol from solid wastes. After studying Brazil's municipal wastes, Wang *et al.* [34] concluded that the main part of the latter consists of paper, cardboard, etc. which have good potentials to be turned into bioethanol. Moulod *et al.* [20] studied the economic and technical aspects of solid oxide fuel cells (SOFCs). These fuel cells powered by biogas from municipal solid wastes, as a case study in Tehran. Kesharwani *et al.* [14] concluded that producing liquid biofuel, especially bioethanol, from municipal solid wastes is quite attractive and nature-friendly. As a clear result, there are no papers wherein bioethanol SC design and, hence, production of biofuel from municipal solid wastes have been addressed through mathematical modeling; therefore, this issue has been dealt with in the present paper.

A very serious reason why biofuels are addressed in the related papers is to reduce the pollution caused by the consumption of fossil fuels; therefore, considering the environmental aspect of the sustainable development in the decisions of this area is quite important. However, papers that have addressed this issue in their models are quite limited. Osmani and Zhang [22] tried to minimize the emission of polluting gases by entering the related factors in the objective function of their bioethanol producing model. While presenting a mathematical model for the design of the bioethanol SC using some constraint, Gonela *et al.* [11] added the environmental considerations to their model. Sadhukhan and Ng [28] addressed the ecological sustainability criteria assessment of bio-oil-based biofuel systems. Sustainability Indicators for Chemical Processes such as Biodiesel Case Study are also studied by Ruiz-Mercado *et al.* [27]. Accordingly, the present paper has considered the ecological aspect of the sustainable development in the SC design using the second objective function of a bi-objective mathematical model, which is considered as one of its contribution [3].

To locate facilities in SC design models, usually, some potential points are first defined as a set of possible solutions, and then the best one is selected through mathematical modeling. But, in many cases, papers do not usually specify how the potential points have been selected because the work does not have a mathematical basis and is usually based on the experts' opinions. However, it is possible to use some mathematical methods to rank and select different choices. In this regard, there are only two papers (introduced next) with such features. In his SC design of extracting biodiesel from microalgae, Mohseni and coworkers [18, 19] has used the GIS to define appropriate places for planting algae. Babazadeh *et al.* [3] have used the "Data Envelopment Analysis" model to rank Iran provinces to plant Jatrofa for biodiesel production. Sustainable development and sustainability assessment have been of great interest to both academe and practitioners in the past decades. Zhou *et al.* [36] have presented a review of the literature on data envelopment analysis (DEA) applications in sustainability using citation-based approaches. They classify DEA methods used in sustainability research into six main groups and categorized existing studies into them. As Figure 1 shows, the most frequently used DEA methods in sustainability study are traditional DEA models (*e.g.*, CCR and BCC models).

In the present study, too, use has been made of a powerful tool called "cross-efficiency data envelopment analysis" to define and rank a set of potential bio-refinery. Cross efficiency approach: The idea of the Cross efficiency approach that alleviates the weak discrimination of the basic DEA model could be explained in two steps. Firstly, the basic DEA analysis is carried out and for each DMU, optimal weights of inputs and outputs are calculated. In the next step so called cross-efficiency matrix C has to be constructed. Matrix C is the ratio of outputs and inputs of the DMU_j, weighted by the optimal weights of DMU_i. This means that column j consists of the efficiencies of the DMU_j measured by optimal weights of DMU_i. Doyle and green [9] in your study have demonstrated how to drive simple efficiency and cross-efficiency, and identify each with the intuitive notions of self-appraisal and peer-appraisal, respectively. In the present study, the weighted sum method is also used to calculate efficiency.

Accordingly, it is possible to rank and select points by defining and using some indicators and, on their bases, determine the candidate provinces for the construction of bio-refinery and reduce the number of input points to the problem's SC design model. In addition, many technical aspects that affect the SC design (*e.g.*, environmental issues) and their considering in the network design sometimes causes the model complexity, can

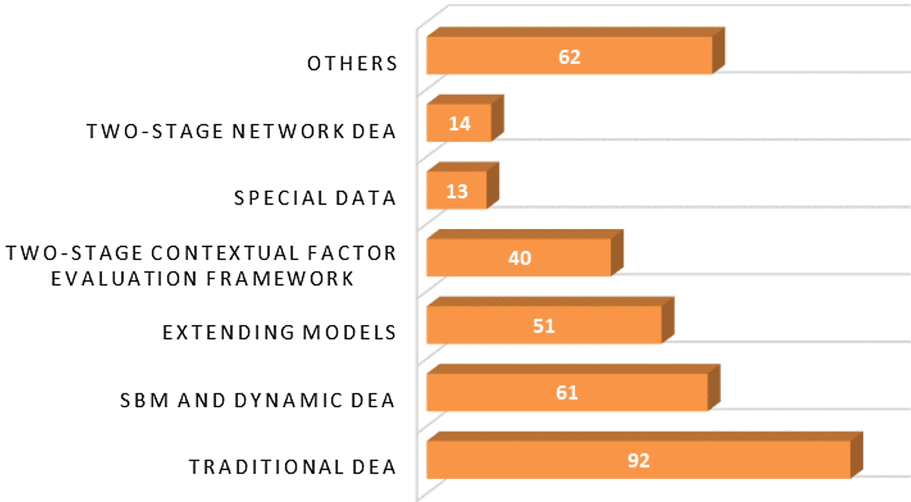

FIGURE 1. Classify DEA methods used in the sustainability research.

affect the decision making through this method and its related indices. Ferreira and Trierweiler [10] and Osmani and Zhang [22, 23] have considered the social aspect of the sustainable development in their models proposed for the bioethanol SC design; however, there gaps in this area of the sustainable development for the filling of which effort has been made in this research to focus on it through presenting some ecological indicators and using the DEA method.

Presently, the international SC design and export/import law consideration in the mathematical models of the network design are research areas that have not received proper attention by researchers. Specifically, among the bioethanol SC models, there is no one that has addressed the international logistics issue, whereas in some cases importing raw materials from abroad is a necessity. Hence, a contribution in the model proposed in this research is the inclusion of the export/import issues in the SC model based on Iranian laws and regulations. Next, a bi-objective model has been proposed for the design of an international and sustainable SC for the production of biofuels from the cellulosic part of the municipal wastes. Sanction-caused disruptions, which are an inseparable part of importing raw materials in many countries, including Iran have also been considered in the model. Meanwhile, to define a set of potential points to construct facilities, the use has been made of the DEA.

In summary, the contributions of this study are: (1) Using municipal solid wastes to produce biofuel, and formulating a mathematical programming model to design this MSW-to-biofuel supply network; (2) Taking ecological indicators of the sustainable development into account by proposing a bi-objective model for MSW-to-biofuel supply chain; (3) defining ecological and social indicators to be used by cross-efficiency DEA, in order to identify sustainable potential points to configure this SC; (4) Studying the international logistics issue of raw material exports/imports; and (5) Appling the real data of the case study to analyze the results of this model.

3. Problem statement of MSW2B-SCN

As mentioned before, in this paper, a MSW-to-Biofuel supply network (MSW2B-SCN) is considered. A typical biofuel supply chain is presented in Figure 2. The MSW2B-SCN consists of three echelons of supply (collect municipal cellulosic wastes), bio-refinery, and distribution centers, and biofuels are combinations of bioethanol and petrol. For more details, assumptions of this SCN design model are presented, which are:

- The bio-refinery and internal distribution centers are to be located.

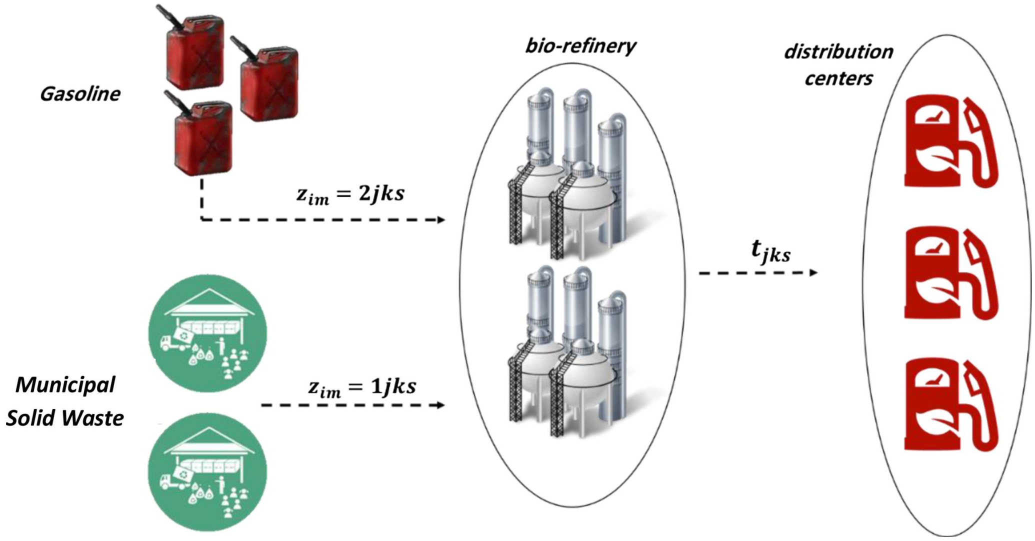

FIGURE 2. A typical biofuel supply chain from MSW.

- There are different types of raw material.
- Only one final product (biofuel) is assumed.
- Each Supplier provide different type of raw materials.
- Raw material imports are assumed because some supply centers are in other countries.
- The model is single-period and deterministic.
- In every bio-refinery, not only bioethanol is produced from cellulosic wastes, but it is also mixed with petrol to produce liquid biofuel for transportation.
- The number of constructible bio-refinery is limited to the allocated budget.
- Every bio-refinery has a minimum and maximum capacity.
- Final product exports are assumed as some distribution centers are in other countries.
- Demands for biofuels are known.
- Demands are divisible at the level of both the production and distribution centers.
- According to the customs laws of Iran, import taxes are determined based on the incoterms CIF terms; export laws ensure that the production value added tax and the customs import tax (for exporting products) should be returned; bonuses are allotted to exporting products.
- The foreign-supplied raw material transportation is divided into domestic and foreign; the former is done through roads and the latter by ship; therefore, mode selection is excluded.
- Clearance of the imported raw materials is assumed to be done at only one port for each country; therefore, one-to-one communication between each foreign supply center and the related domestic port (and then from that port to the production centers) is possible; route selection is, hence, not an issue.
- In supplying raw materials, full disruption is considered.

3.1. Mathematical programing model of MSW2B-SCN

To understand this model, better sets, parameters, and variables of this mathematical programming model are addressed in Tables 1–3.

TABLE 1. Sets.

Notation	Description
i	Set of supply centers.
i_1	Set of raw materials.
i_2	Set of internal supply centers.
m	Set of external supply centers.
j	Set of potential points of bio-refinery.
k	Set of potential points of biofuel distribution.
k_1	Set of internal distribution centers.
k_2	Set of external distribution centers.
s	Set of disruption (sanction) scenarios.

3.1.1. Model constraints

Capacity constraints

For each supply center, there is a predefined limited capacity meaning that its total outflow is not to exceed its availability. Sanctions have also been considered through using in the disruption parameter.

$$\sum_{j,k} z_{imjks} \leq \mathrm{disr}_{is}\ \mathrm{avail}_{im} \qquad \forall i, m, s. \tag{3.1}$$

Each bio-refinery has minimum/maximum capacities beyond which the production is not allowed.

$$\sum_{k} t_{jks} \geq \mathrm{cap}_j^{\min} x_j \qquad \forall j, s \tag{3.2}$$

$$\sum_{k} t_{jks} \leq \mathrm{cap}_j^{\max} x_j \qquad \forall j, s. \tag{3.3}$$

Demand constraints

Constraints (3.4) and (3.5) ensure that for domestic/foreign distribution centers, their inflow may not exceed their maximum demand.

$$\sum_{j} t_{jk_1s} \leq \mathrm{Drate}_{k_1} \mathrm{dem}_{k_1} y_{k_1} \qquad \forall k_1, s \tag{3.4}$$

$$\sum_{j} t_{jk_2s} \leq \mathrm{Drate}_{k_2} \mathrm{dem}_{k_2} \qquad \forall k_2, s. \tag{3.5}$$

Balance constraint

In each scenario, and in every bio-refinery, there should be an inflow-outflow balance for each material; this is checked through the following relation:

$$\sum_{i} z_{imjks} = \mathrm{comp}_m t_{jks} \quad \forall j, k, m, s. \tag{3.6}$$

Budget and non-negativity constraint

Maximum budget allotted for the construction of biofuel production centers is known

$$\sum_{j} \mathrm{in}\, v \cos \mathrm{tr}_j x_j \leq \mathrm{buger} \qquad \forall j, k, m, s \tag{3.7}$$

$$x_j, y_{k_1} \in \{0, 1\} \qquad \forall j, k, m, s \tag{3.8}$$

$$t_{jks}, z_{imjks} \geq 0 \qquad \forall j, k, m, s. \tag{3.9}$$

TABLE 2. Parameters.

Notation	Description
avail_{im}	Type m raw material available in supply center i
$\mathrm{capr}_j^{\min}$	Minimum capacity of bio-refinery j
$\mathrm{capr}_j^{\max}$	Maximum capacity of bio-refinery j
dem_k	Petrol demand at distribution center k
Drate_k	Percent petrol demand to be covered by biofuels
idistr_{ji}	Distance from internal supply center i, or from corresponding port of foreign supply center i, bio-refinery j (import of imported products is done *via* only one port)
edistr_{i_2}	Distance from external supply center i to its corresponding port (imported products related to each supplier enter/clear through only one port)
Erate	Currency exchange rate of the desired foreign country (to the base currency unit)
$\mathrm{itcostr}_m$	internal transportation cost of raw material m from supply centers to bio-refinery per unit distance and unit flow based on the desired foreign country's currency unit
$\mathrm{etcostr}_m$	external transportation cost of raw material m from supply centers to production centers per unit distance and unit flow based on the desired foreign country's currency unit
$\mathrm{invcostr}_j$	Fixed investment cost of locating bio-refinery j based on the desired foreign country's currency unit
pcost_j	Variable production cost at bio-refinery j based on the desired foreign country's currency unit
idistd_{jk}	Distance between bio-refinery j and distribution center k for internal distribution centers and exporting ports corresponding to external distribution centers
edistd_{k_2}	Distance between exporting port corresponding to distribution center k_2 in the country of origin and distribution center k_2 in the country of destination
itcostd	internal transportation cost of unit biofuel per unit distance and unit flow based on the desired foreign country's currency unit
etcostd	External transportation cost of unit biofuel per unit distance and unit flow based on the desired foreign country's currency unit
$\mathrm{finvcost}_{k_1}$	Fixed investment cost of internal distribution center k
tax_j	VAT tariff rate at bio-refinery j
tarif_m	Import tariff rate for raw material type m
g	Rate of export bonus
bugr	Budget ceiling for construction of bio-refinery based on the desired foreign country's currency unit
comp_m	Percent raw material m required to produce a unit biofuel
disr_{is}	Disruption (Sanction) parameter for supplier i in scenario S (1, if a sanction is not imposed, and 0, otherwise)
goal_{k_1}	goal defined based on the country strategies to reduce CO_2 emission caused by road transportation
$\mathrm{emition}_{k_1}$	CO_2 emission caused by consuming petrol in road transportation
dec	Reduction in CO_2 emission if biofuel is used instead of petrol in road transportation
msw_{i_1}	Percent (from country's total) municipal cellulosic waste allotted to internal supply centers
pur_{im}	Purchasing Price of raw material m from supplier i based on the desired foreign country's currency unit
sel_k	Selling Price of biofuels to distribution centers based on the desired foreign country's currency unit
w_1	Weight of the first objective function (profit)
w_2	Weight of the second objective function (environmental)
d_j	Efficiency of potential production center j obtained from DEA model output
prob_s	Occurrence probability of scenario S
PI_{k_1}	Weight of internal demand center k_1 in achieving the air pollution reduction goal

TABLE 3. Decision variables.

Notation	Description
x_{j}	0–1 variable of locating bio-refinery j (1, if located and 0, otherwise)
y_{k_1}	0–1 variable of locating distribution center k_1 (1, if located and 0, otherwise)
z_{imjks}	Raw material m flow from supplier i to bio-refinery j to produce to meet the demand of distribution center k in scenario S
t_{jks}	Variable of rate of biofuel flow from production center j to distribution center k in scenario S

3.1.2. First objective function: the economic performance of the model

Fixed investment costs

These consist of the fixed investment cost of the internal distribution center and bio-refinery. The point worth mentioning is that, here, use is made of the DEA model output as an effective coefficient in locating bio-refinery; a province with higher rank has more priority. Since this is multiplied by the cost-related term, the final objective function (which is profit) is multiplied by the inverse of this index.

$$\sum_{j} \frac{1}{d_j} \mathrm{invcostr}_j \mathrm{Erate} \times x_j + \sum_{k_1} \mathrm{finvcost}_{k_1} \mathrm{Erate} \times y_{k_1}. \tag{3.10}$$

Purchasing costs of raw materials

Whole purchasing costs of all raw materials from all suppliers in all scenarios is as follows:

$$\sum_{m} \sum_{i} \sum_{k} \sum_{j} \sum_{s} \mathrm{pur}_{im} \mathrm{Erate} \times \mathrm{prob}_s z_{imjks}. \tag{3.11}$$

Production costs at bio-refinery

The production volume is multiplied by the Production costs and also value added tax:

$$\sum_{j} \sum_{k} \sum_{s} \mathrm{Erate} \left(p\,\mathrm{cost}_j + \mathrm{sel}_k \mathrm{tax}_j \right) \mathrm{prob}_s t_{jks}. \tag{3.12}$$

Transportation costs

These items consist of four main parts: (1) transportation cost of raw materials from an external supplier. This transportation is both internal and external, and to calculate the related costs the flow volume is multiplied by the related unit transportation cost and the origin-destination distance (as mentioned before, foreign suppliers send raw materials to only one port), (2) transportation cost of raw materials from an internal supplier which are found through multiplying the flow volume by the unit transportation cost and distance between the two nodes, (3) cost of exporting biofuels to other countries which are found as in (1), and (4) costs of delivering biofuels to internal distribution center which are found as in (2).

$$\sum_{m} \sum_{i_2} \sum_{k} \sum_{j} \sum_{s} \mathrm{Erate} \left(\mathrm{edistr}_{i_2} \mathrm{et\ cos\ tr}_m + \mathrm{idistr}_{i_2 j} \mathrm{it\ cos\ tr}_m \right) \mathrm{prob}_s z_{i_2 mjks}$$
$$+ \sum_{m} \sum_{i_1} \sum_{k} \sum_{j} \sum_{s} \mathrm{Erate} \left(\mathrm{idistr}_{i_1 j} \mathrm{it\ cos\ tr}_m \right) \mathrm{prob}_s z_{i_{1mjks}}$$

$$+\sum_{j}\sum_{k_2}\sum_{s}\text{Erate}\left(\text{idistd}_{jk_2}\text{it cos td}+\text{edistd}_{k_2}\text{it cos td}\right)\times \text{prob}_s t_{jk_2s}$$
$$+\sum_{j}\sum_{k_1}\sum_{s}\text{Erate}\times \text{idistd}_{jk_1}\text{it cos td}\times \text{prob}_s t_{jk_1s}. \quad (3.13)$$

Imports customs costs

These are mandatory for raw materials imported from foreign countries and are calculated based on the incoterm CIF term as a percent of the total costs of purchasing and shipment to the port of the destination country; in the following relation, this term has been multiplied by the customs percent and fee.

$$\sum_{m}\sum_{i_2}\sum_{k}\sum_{j}\sum_{s}\text{Erate}\left(\text{pur}_{i_2m}+\text{edistr}_{i_2}\text{et cos tr}_m\right)\text{tarif}_m\text{prob}_s z_{i_2mjks}. \quad (3.14)$$

Income from selling biofuels

The total income is obtained through multiplying the total sale by the sale price; this also needs to be multiplied by the scenario occurrence probability.

$$\sum_{j}\sum_{k}\sum_{s}\text{Erate}\times \text{sel}_k\text{prob}_s t_{jks}. \quad (3.15)$$

Income from production VAT/customs duties refund and exports bonus

The first part of equation (3.16) deals with the income from the production VAT and export bonus. The latter is some percent of the export price and the former, which is a percent of sale, is a refund for foreign sale or export. The second part of equation (3.16) deals with the refund of the import customs fees. In this part, the refund is only for cases where foreign suppliers are used to meet the foreign market's demand (which is considered as income in the model).

$$\sum_{j}\sum_{k_2}\sum_{s}\text{Erate}\times \text{sel}_{k_2}\left(g+\text{tax}_j\right)\text{prob}_s t_{jk_2s}+\sum_{m}\sum_{i_2}\sum_{k_2}\sum_{j}\sum_{s}\text{Erate}\left(\text{pur}_{i_{2m}}+\text{edistr}_{i_2}\text{et cos tr}_m\right)$$
$$\times\, \text{tarif}_m\text{prob}_s z_{i_{2mjk_2s}} \quad (3.16)$$

where finally, the first objective function is found from the algebraic sum of the above equations.

3.1.3. Second objective function: the ecological performance of the model

Considering profit, and according to Iran's export-oriented laws, export has priority compared to consumption in the domestic distribution centers. Since there are such incentives as tax refunds and export bonus, the model performance is such that most of the produced biofuel is exported. If capacity allows, it is tried to meet the demand of foreign distribution centers and then meet that of the domestic market. But, since the environmental aspect of the sustainable development is also considered in this study, and the issue of air pollution reduction is quite vital for Iran provinces, effort should be made to give priority to the satisfaction of the domestic needs or, in other words, create a balance between profit and improvement of the domestic ecological indicators.

Therefore, the second objective function has been included in the model which has two major parts. Part one is a response to the need mentioned above and its mechanism is such that a goal is considered to cover the demand of the domestic distribution centers and it is desirable to minimize the distance from this goal as much as possible. It is to be noted that the domestic distribution centers have different importance compared to one another; therefore, they are given weights by applying a coefficient.

Since one main objective of this study is to extract fuel from municipal solid waste to properly manage them, the second part deals with the maximum use of such wastes. Accordingly, by including this part in the second objective function an obligation is created that requires the maximum use of these wastes. This is true only for domestic suppliers and only for waste raw material (not for other types). In this regard, metropolitans with more waste production are ranked higher, and waste allocation for them from the total waste in the country is based on the weight they obtain. The equation is as follows:

$$\min\left(\sum_{k_1}\mathrm{PI}_{k_1}\left(\mathrm{emision}_{k_1}\mathrm{goal}_{k_1}\mathrm{dec}-\sum_j\sum_s \mathrm{prob}_s t_{jk_1s}\right)\right.$$
$$\left.+\sum_{i_1,m=1}\left(\mathrm{avail}_{i_1m}-\sum_s\sum_k\sum_j \mathrm{prob}_s z_{i_1mjks}\right)\mathrm{msw}_{i_1}\right). \quad (3.17)$$

4. Solution method

As discussed before, at the first stage to identify sustainable potential points as the candidates of locations to design this SCN, the sustainable DEA method is employed. Then, the developed bi-objective programming model can be solved to configure the MSW2B supply chain network.

4.1. Using cross-efficiency DEA to identify the potential sustainable set of bio-refinery

As mentioned earlier, it is possible to use a powerful method called the DEA to limit the problem-solution space and also present a scientific method of defining a set of potential solutions for facility locating. Additionally, some indices (economic, social, ecological, etc.) that affect facility locating in the framework of the model criteria, are defined. Accordingly, after defining the related indices, all the possible options are ranked and then some of them with the highest ranks are selected to enter the set of the potential solutions and the model as inputs. In this case the basic model is the DEA-CCR, which is explained in the following.
Where:

Sets

i Inputs.
j Alternative.
r Outputs.

Parameters

x_{ij} Amount of ith input utilized by jth alternative.
y_{rj} Amount of rth output produced by jth alternative.

Variables

v_r Weight of the rth output.
u_i Weight of the ith input.
θ_j Efficiency of the jth alternative.

$$\theta_j=\frac{\sum_r v_r y_{rj}}{\sum_i u_i x_{ij}} \qquad \forall j \quad (4.1)$$

$$\max\theta_0=\frac{\sum_r v_r y_{r0}}{\sum_i u_i x_{i0}} \quad (4.2)$$

$$\frac{\sum_r v_r y_{rj}}{\sum_i u_i x_{ij}}\le 1 \qquad \forall j \quad (4.3)$$

$$v_r,u_i\ge 0 \qquad \forall i,r. \quad (4.4)$$

TABLE 4. Cross-efficiency DEA.

	1	2	...	N
E_{1j}	E_{11}	E_{12}	...	E_{1n}
E_{2j}	E_{21}	E_{22}	...	E_{2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
E_{nj}	E_{n1}	E_{n2}	...	E_{nn}
Average of the efficiency in each columns	$\bar{E}_1$	$\bar{E}_2$	...	E_{nj}

As shown in the above relation, in input-based models, the objective is to maximize output (or efficiency), but since the above model is nonlinear, changes in the following variables are used to linearize it:

$$t = \frac{1}{\sum_i u_i x_{ij}} \tag{4.5}$$

$$tu_i = \vartheta_i \tag{4.6}$$

$$tv_r = \mu_r. \tag{4.7}$$

After substituting the variable changes, the final DEA-CCR model will be as follows:

$$\max \sum_r \mu_r y_{r0} \tag{4.8}$$

$$\sum_i \vartheta_i x_{i0} = 1 \tag{4.9}$$

$$\sum_r \mu_r y_{rj} - \sum_i \vartheta_i x_{ij} \leq 0 \qquad \forall j \tag{4.10}$$

$$\mu_r, \vartheta_i \geq 0 \qquad \forall i, r. \tag{4.11}$$

The criticism applicable to the DEA-CCR method is that if the efficiency of each option is calculated based on its own weight, the efficiency comparison and alternative ranking among them will not sound logical. To solve this problem, the cross-efficiency DEA method can be use according to which first each option's efficiency is calculated by the equation (4.12), based on other options' weights and then Table 4 is formed and after that final efficiency for each alternative is calculated.

$$E_{dj} = \frac{\sum_r \mu_r^{d^*} y_{rj}}{\sum_i v_i^{d^*} x_{ij}} \qquad \forall r, d^* \tag{4.12}$$

where E_{dj} is the efficiency of the ith option based on the weights found from the model solved for option d.

4.2. Bi-objective programming

If $f_1(X)$ and $f_2(X)$ are assumed to be two contradicting objective functions (first of them maximizing and second one minimizing), the general form of the model will be as follows:

$$\begin{aligned} &\min f_2, \max f_1 \\ &\text{s.t.} \\ &\quad AX \leq B \\ &\quad X \geq 0. \end{aligned} \tag{4.13}$$

Under these conditions, first the ideal and anti-ideal values of each objective function should be found alone through relation (4.14), and then, using this definition, relation (4.13) is changed to relation (4.15). Accordingly, the bi-objective model will change to a single objective one through entering each function weight and also descaling.

$$
\begin{aligned}
&f_2^{\max} = f_1^{\max} \\
&f_1^{\min} = f_2^{\min} \qquad (4.14)\\
&\max \left(w_1 \frac{f_1 - f_1^{\min}}{f_1^{\max} - f_1^{\min}} + w_2 \frac{f_2^{\max} - f_2}{f_2^{\max} - f_2^{\min}} \right) \qquad (4.15)\\
&\text{s.t.}\\
&\quad AX \leq B\\
&\quad X \geq 0.
\end{aligned}
$$

In the model proposed in this study, the first objective function is related to profit, so it should be maximized, and the second deals with the distance from the set goal, so it should be minimized; this bi-objective model can be made single objective using relation (4.15).

5. Case study

As mentioned before, to validate the proposed model, the use was made of Iran's real data. Next, some details will be provided regarding the numerical values of the parameters used in the model.

5.1. Sustainable cross efficiency DEA model

In using any DEA method, it is necessary to first define the indicators and options and then rank the latter accordingly. Since the population affects many parameters (waste volume, fuel demand and hence environmental pollution, etc.), it has been defined as a non-compensatory indicator; provinces with a higher population are ranked higher. Accordingly, and based on the data of Iran Statistics Center, 15 Iranian provinces with higher populations have been defined as the problem options. Next, using experts' opinions and library sources, some indicators that can be effective in the selection and ranking of these 15 provinces have been defined as follows:
Economic indicators:

– Land price.
– Production VAT.

Ecological indicators:

– Weight of the municipal cellulosic wastes (paper, cardboard, newspaper, etc.).
– Accessible land for facility construction.
– Road transportation fuel consumption.
– Air pollution.

Social indicators:

– Human development index.
– Unemployment rate.
– Economic welfare level.

In the first step to use the data envelopment analysis method, the criteria and indicators should be divided into inputs and outputs category. In some cases, this type of classification is possible on criteria, and the output and input concept can be separated. In other cases, it is not possible to separated criteria into the input and output category. The common approach used is to consider any index that is desirable to minimize input and any index that is desirable to maximize output. Table 5 shows the options (provinces) in different indices (data in this table have been gathered from the sites of Iran Statistics Center and Department of Environment, and also the Energy Balance Sheet). This sustainable DEA method can easily be employed in other industries by identifying new suitable indicators.

5.2. MSW2B SCN: economic objective function

The raw materials considered in this study are petrol and municipal solid waste (assumed to be supplied from only foreign and only domestic suppliers respectively); the only output product is biofuel which is 80% petrol and 20% bioethanol 300 liters of which are produced from 1 ton of cellulosic waste on average. It is necessary to first specify the location sets of the supply, production, and distribution centers. Based on the statistics of the "Waste Management Organization" in each province and the outputs of the DEA model discussed earlier, 5 provinces with the highest cellulosic waste have been defined as the supply centers, 5 with the highest efficiency have been introduced as the potential production centers, and finally 5 with the highest petrol consumption in the road transportation have been considered as the distribution centers (Tab. 6).

Three scenarios have been defined for sanctions; in the first, sanctions are none, and suppliers are all accessible, in the second, France and Netherland are eliminated from the suppliers' list, and in the third, in addition to France, the UAE too, as the greatest supplier of Iran petrol, is faced with disruptions; the occurrence probability for the three scenarios is similar and equal to 0.333.

Table 7 shows the maximum raw material supply based on the statistics of each province "Waste Management Organization" and the Balance Sheet published by the "Ministry of Petroleum of Iran".

The cost of purchasing waste (raw material) is 0.0625 \$/1000 tons (equal for all suppliers), and that of petrol is 1.8 m\$/1 million liters. Calculating raw material/biofuel transportation costs necessitates knowing distances between facilities which are provided in Tables 8–11. As mentioned earlier, only one import/export port is assumed for every supply/distribution center; the raw material/final product flow is first carried to this port and then sent to the final destination.

The assumption is that foreign transport is through the sea and the domestic transport is *via* road. The related petrol/biofuel transportation costs, based on the Iran Energy Balance Sheet, are given in Table 12. It has also been assumed that 20% of the fuel needed for road transportation is provided by biofuels. Their related costs are given in Table 13 (based on the same reference).

5.3. MSW2B SCN: environmental objective function

In the second part of the second objective function, to give priority to provinces with higher waste production rates, use has been made of a weight coefficient found from the ratio of that province's cellulosic waste to the total value for the country (Tab. 14).

In the first part of the environmental objective function, to give priority (for biofuel allocation) to provinces with higher pollution rates, use has been made of a weight coefficient which is the ratio of the CO_2 emitted due to petrol consumption in road transportation of each distribution center to the total value for the country; the related data has been found using the values presented in the 2013 report of Iran Energy Balance Sheet (Tab. 15). Finally, to define some objectives for allocating biofuels to domestic distribution centers, use has been made of Iran's commitments in the "Treaty of Paris".

6. Numerical results and sensitivity analyses

All the results addressed in the following lines have been obtained using the CPLEX and GAMS 24.1.2 on a 4-core, 2.2 GH pc with 6 GB RAM.

TABLE 5. Provinces and their ranks in each index.

		Output							Input	
	Province	Accessible land for facility construction	Wt. of municipal solid waste (annual, ton)	Household annual average income (rial)	Unemployment rate	Air pollution (No of unhealthy days based on AQI)	Fuel consumption (ml)	Production VAT	Land price (1000 R/M^2)	Human Development Index (HDI)
1	Tehran	0.0011	26 500	403 056 795	11.6	160	4953	1	53 916	0.812
2	Khor. Razavi	0.0198	58 084	217 899 854	8.7	130	1753	1	2813	0.711
3	Esfahan	0.0219	72 702	300 387 505	13.8	300	1813	1	7883	0.763
4	Fars	0.0267	416 800	266 394 398	16.8	25	1618	1	5615	0.737
5	Khoozestan	0.0141	67 523	252 751 715	12.8	160	1246	1	3887	0.73
6	East Azerb.	0.0123	55 497	33 167 502	12.5	75	980	1	3962	0.713
7	West Azerb.	0.0121	45 901	206 013 985	11.1	80	772	1	5713	0.662
8	Mazandaran	0.0057	100 028	258 106 897	9.8	30	1321	1	3607	0.755
9	Kerman	0.0021	43 791	248 153 911	7.8	100	1052	0	3229	0.712
10	Sistan & Bal.	0.0717	37 761	155 483 628	10.5	98	807	0	4122	0.587
11	Gilan		36 965	250 081 914	15.6	35	906	1	3548	0.735
12	Alborz		35 946	277 796 495	14.9	80	892	1	5679	0.76
13	Golestan	0.0115	26 478	223 696 017	8.9	25	407	1	2695	0.692
14	Hamedan	0.011	26 198	208 837 002	9.7	50	438	1	3734	0.701
15	Lorestan	0.0161	26 138	172 736 814	20.2	75	379	1	2408	0.679

Table 6. The supply, production, and distribution centers of the SC design model.

Facility	Foreign				Domestic				
Supply	Netherland	France	India	UAE	Khoozastan	Esfahan	Mazandaran	Tehran	Fars
Bio refinery					Sistan & Baloochestan	Khoozastan	Fars	Esfahan	Tehran
DC		Saudi Arabia	India	China	Mazandaran	Fars	Khorasan	Esfahan	Tehran

Table 7. Maximum allowable flow from each supplier (avail_{im}).

	Gasoline (Million liters. Annually)	Municipal solid waste (Thousand tons. Annually)
Fars	0	417
Tehran	0	264
Mazandaran	0	100
Isfahan	0	73
Khuzestan	0	68
United Arab Emirates	3154	0
India	310	0
France	40	0
Netherlands	20	0

Table 8. Distance between a foreign supply center and Bandar Abbas as the petrol import terminal.

	Kilometer
United Arab Emirates	250
India	1937
France	9174
Netherlands	20 592

Table 9. Distance between each domestic supply center or corresponding port of the foreign supply center and each production center (idistr_{ji}).

	Bandar Abbas (Equivalent to five external supply center)	Khuzestan	Isfahan	Mazandaran	Tehran	Fars
Tehran	1501	881	414	250	0	895
Isfahan	1082	765	0	664	414	132
Fars	601	568	481	1145	895	0
Khuzestan	1169	0	765	1131	881	568
Sistan and Baluchestan	1039	1906	1244	1694	1605	1338

TABLE 10. Distance between a foreign distribution center and Bandar Abbas as the petrol export terminal.

	Kilometer
China	8969
India	1937
Saudi Arabia	711

TABLE 11. Distance between each domestic distribution center or corresponding port of the foreign distribution center and each production center.

	Bandar Abbas	Mazandaran	Fars	Khorasan	Isfahan	Tehran
Tehran	1501	250	895	924	414	0
Isfahan	1082	664	481	1238	0	414
Fars	601	1145	0	1819	481	895
Khuzestan	1169	1131	568	1805	765	881
Sistan and Baluchestan	1039	1694	1338	1001	1244	1605

TABLE 12. Raw material/biofuel transportation costs.

	External (Sea)	Internal (Road)
Municipal solid waste (Millions dollars. Thousand ton kilometer)	0.00004	0.00007
Gasoline (Millionsdollars.million liters kilometer)	0.000011	0.000019
Biofuel (Millions dollars. million liters kilometer)	0.000015	0.000025

TABLE 13. Distribution centers' demands for biofuels.

Distribution centers	Saudi Arabia	India	China	Mazandaran	Fars	Khorasan	Isfahan	Tehran
Demand	800	800	800	264	324	351	363	991

TABLE 14. Rate of each province cellulosic waste compared with that of the whole country.

Province	Fars	Tehran	Mazandaran	Esfahan	Khoozestan
Rate	0.2977	0.1889	0.0714	0.0519	0.0482

TABLE 15. Other parameter.

Province	Mazandaran	Fars	Khorasan	Isfahan	Tehran
goal_{k_1}	59	73	78	81	221
PI_{k_1}	0.053	0.065	0.070	0.0749	0.198

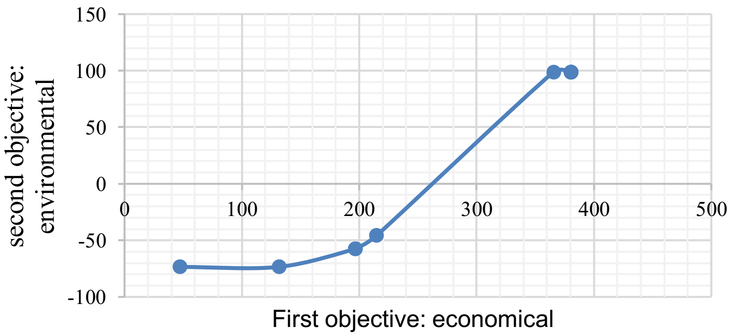

FIGURE 3. Pareto graph of the bi-objective (economic-environmental) model.

6.1. Numerical results of the cross-efficiency DEA model

First, an efficiency value is found for each option (province) by solving the input-based DEA-CCR model, and the weights of the indices are specified as the model variables. Table 16 shows the results found from each model solution for each option.

A criterion through which DEA models can be evaluated and validated is efficiency the value of which is not to exceed 1; results in Table 16 also approve this point.

The DEA-CCR models do not usually automatically provide the decision-maker with the ability to prioritize and select the option; use is usually made of the cross-efficiency method to solve this problem. Table 17 has presented cross efficiency while the bottom line of this table, which is the arithmetic mean of each column, indicates the final efficiency or the ranking of each option or province. Finally, the numbers in the bottom row of Table 18, which is the same rank of each province, are shown in descending order and in Table 17, which are prioritized by the different provinces according to their rank; the conditions governing the issue selected a number of them.

6.2. Pareto solutions

First, the bi-objective model proposed in this study is changed to a single-objective model considering the issues in Section 4 entitled "Bi-objective Programming", and then its Pareto graph is drawn by allotting different weights to the first objective function.

A point important in multi-objective programming is the contradiction among different objective functions meaning that improvement in one worsens the other; this should be observed in the Pareto graph; in Figure 3, the Pareto graph of the first objective function (or the economic aspect) has been drawn by changing its weight. As shown, the more the weight becomes, the more will be the chain profit, but with this increase, the effects of the second (environmental) objective function weaken, and its situation becomes worse.

6.3. Sensitivity analysis

Figure 4 shows the first objective function's weight increase effects on air pollution reduction. Since the generation of 1 megajoule energy, if biofuel is substituted for ordinary petrol, will averagely cause about 88 gr reduction in the CO_2 emission, this figure and also the total flow of biofuel used in domestic distribution centers for changes in the first objective function have been used to draw Figure 3. In scenarios 1 and 2, first, the environmental aspect will dominate with an increase in the weight of the first objective function, because the weight of the second objective function is large, and the whole produced biofuel is consumed domestically; the figure is horizontal in this case. Then, the model reacts to the weight increase, and part of the production is exported; hence, the domestic consumption and the resulting CO_2 emission are reduced. After a certain point, the export-oriented term will dominate, and all the produced biofuel is exported; the domestic consumption

Table 16. Model solution results for different options.

Province	Input						Output			
	Efficiency	Human Development Index (HDI)	Land price (1000 R/M^2)	Production VAT	Fuel consumption (ml)	Air pollution (No of unhealthy days based on AQI)	Unemployment rate	Household annual average income (rial)	Wt. of municipal solid waste (annual, ton)	Accessible land for facility construction
Tehran	1	0	0	1	0.446	0	0.966	0	0	0
Khorasan-e Razavi	1	0	19.231	0	0	2.309	0	0	0	0
Esfahan	1	0	6.032	0.119	0	1	0	0	0	0
Fars	1	0.0003404	1.038	0.583	1.347	0	0	0	0.423	0.368
Khoozestan	1	0.0000893	3.25	0.766	1.039	0.064	0.589	0.529	0	0
Easst Azerbaijan	0.837	0.0002284	2.382	0.826	1.685	0	0.799	0	0.065	0
West Azerbaijan	0.843	1.143	0.642	0	0	0	0.514	1.097	0	0
Mazandaran	1	0.913	2.249	0	0	0	0.02	1.547	0	0
Kerman	1	0.956	2.697	0	0	0	0.21	1.137	0	0.989
Sistan & Baloochestan	1	0.75	0.598	0	0	0	0.273	0.549	0	0.646
Gilan	1	1.047	0.8	0	0	0	0.399	0.707	0.208	0.87
Alborz	1	0.865	0.565	0.131	0	0	0.475	0.942	0	0
Golestan	1	0.925	4.23	0	0	0	0.037	1.741	0	0.108
Hamedan	0.928	0.968	2.384	0	0	0	0	1.21	0.226	1.041
Lorestan	1	1.038	2.929	0	0	0	0.238	1.202	0.135	1.056

TABLE 17. Cross efficiency.

	Tehran	Khorasan-e Razavi	Esfahan	Fars	Khoozestan	Easst Azerbaijan	West Azerbaijan	Mazandaran	Kerman	Sistan & Baloochestan	Gilan	Alborz	Golestan	Hamedan	Lorestan
Tehran	1	0.574	0.823	0.949	0.724	0.686	0.6	0.587	0.467	0.575	0.827	0.793	0.462	0.502	1
Khorasan-e Razavi	1.23	0.999	2.309	0.191	1.23	0.577	0.616	0.23	0.768	0.755	0.27	0.616	0.191	0.385	0.577
Esfahan	0.533	0.433	1	0.083	0.533	0.25	0.267	0.1	0.333	0.327	0.117	0.267	0.083	0.167	0.25
Fars	1.621	0.637	0.678	1	0.479	0.386	0.318	0.501	0.645	0.626	0.652	0.289	0.195	0.441	0.213
Khoozestan	1.94	0.935	1.24	1.184	1	0.629	0.773	0.908	0.501	0.7	0.98	1	0.643	0.658	0.911
Easst Azerbai-jan	2.184	0.949	1.173	1.28	0.94	0.836	0.709	0.853	0.672	0.696	0.983	0.898	0.494	0.572	0.932
West Azerbai-jan	1.392	0.813	1.168	1.152	1.013	0.408	0.843	0.951	0.266	0.69	1.076	1.135	0.835	0.814	0.984
Mazandaran	1.558	0.844	1.166	1.039	0.982	0.139	0.801	0.999	0.103	0.607	0.974	1.08	0.867	0.81	0.683
Kerman	1.272	0.977	1.29214 1.294	1.04	0.393	0.863	0.937	1	1.537	0.945	0.967	0.881	0.841	0.92	
Sistan & Baloochestan	0.715	0.592	0.792	0.83	0.644	0.325	0.539	0.554	0.693	0.999	0.602	0.598	0.528	0.514	0.653
Gilan	1.081	0.822	1.1 1.33	0.901	0.482	0.75	0.79	0.966	1.369	1	0.824	0.72	0.821	0.911	
Alborz	1.214	0.713	1.026	1.017	0.891	0.371	0.742	0.833	0.241	0.61	0.95	0.999	0.732	0.715	0.879
Golestan	1.763	0.985	1.355	1.221	1.136	0.184	0.928	1.143	0.214	0.799	1.116	1.229	0.999	0.936	0.808
Hamedan	1.369	0.972	1.258	1.413	1	0.308	0.8199 0.942	0.991	1.528	1.033	0.883	0.852	0.928	0.767	
Lorestan	1.44	1.061	1.403	1.52	1.134	0.445	0.938	1.0322 1.086	1.656	1.132	1.046	0.949	0.983	0.999	
Average	1.354	0.82	1.185	1.034	0.91	0.428	0.7 0.757	0.596	0.898	0.844	0.842	0.629	0.673	0.7662	

TABLE 18. Options' cross-efficiency values.

	Province	Efficiency
1	Tehran	1.3545103
1	Isfahan	1.1859023
2	Fars	1.0340397
3	Khoozestan	0.9102202
4	Systan	0.8985983
5	Gilan	0.8441603
6	Alborz	0.8422707
7	Khorasan Razavi	0.8208692
8	Lorestan	0.7662513
9	Mazandaran	0.7577174
10	Azarbaijan Gharbi	0.7008977
11	Hamedan	0.6730419
12	Golestan	0.6293066
13	Kerman	0.5969616
14	Azarbaijan Sharghi	0.4282463

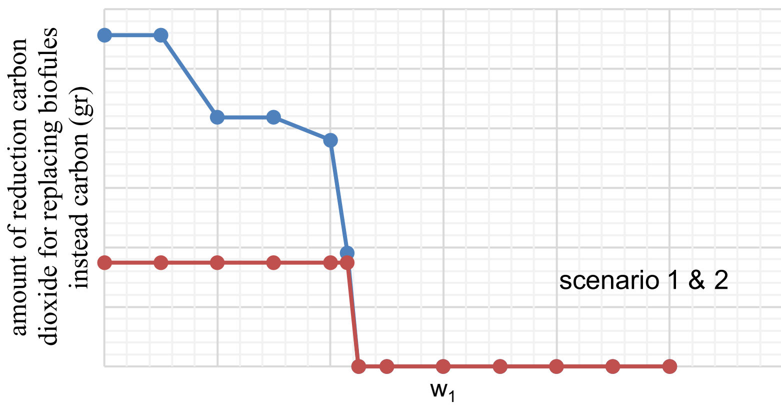

FIGURE 4. CO_2 reduction variations instead of substituting biofuel for ordinary petrol for weight variations of the first objective function in all 3 scenarios.

and the resulting CO_2 emission will considerably drop. The behavior of this figure is easily justifiable with the Pareto graph.

7. Conclusion

This paper presented a two-phase approach based on DEA and an SC design model of extracting second-generation ethanol from municipal cellulosic solid wastes as an additive to ordinary petrol and production of road transportation liquid biofuel to have an eco-friendly energy resource.

In the proposed model, first the economic, ecological, and social indicators are identified as the main criteria of sustainable cross-efficiency DEA model. The use has been made of this DEA model to give priority of candidate locations of facilities in this supply network. Optimization of cultivation locations of municipal solid waste plays a vital role in the success of municipal solid waste projects. This paper addresses the location optimization problem of MSW, considering the most important drivers of sustainable development. Computational results show that the proposed approach can be used a powerful tool for location optimization of MSW. Obtained results are verified and validated by the MSW belt areas. Also, it is concluded that Iran has a great ecological conditions for MSW utilization.

Finally, a bi-objective (economic-environmental) model has been proposed that can create a balance, based on the government decisions and strategies, between the export-oriented profit and environmental interests earned through the municipal solid waste-to-biofuel supply chain network (MSW2B-SCN) design. The results revealed that since the generation of 1-megajoule energy, if biofuel is substituted for ordinary petrol, it will averagely cause about 88 gr reduction in the CO_2 emission. Also, in solving the two-objective model, the first-objective function is more sensitive to weight than the second one.

To the best of our knowledge, this paper is one of the primary efforts on the MSWSCND problem, and its literature is still in infancy. Therefore, to contribute the proposed approach, there is still a broad field of promising avenues for researchers. Studying more SC design levels to include different municipal waste management levels, considering uncertainty in different SC parameters (demand, accessible raw material, etc.) and using robust programming to face uncertainties are recommended.

References

[1] H. An, W.E. Wilhelm and S.W. Searcy, A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. *Bioresour. Technol.* **102** (2011) 7860–7870.

[2] A. Azadeh, H.V. Arani and H. Dashti, A stochastic programming approach towards optimization of biofuel supply chain. *Energy.* **76** (2014) 513–525.

[3] R. Babazadeh, J. Razmi, M.S. Pishvaee and M. Rabbani, A non-radial DEA model for location optimization of Jatropha curcas L. Cultivation. *Ind. Crops Prod.* **69** (2015) 197–203.

[4] Ş.Y. Balaman and H. Selim, A network design model for biomass to energy supply chains with anaerobic digestion systems. *Appl. Energy* **130** (2014) 289–304.

[5] Ş.Y. Balaman and H. Selim, A fuzzy multiobjective linear programming model for design and management of anaerobic digestion based bioenergy supply chains. *Energy* **74** (2014) 928–940.

[6] G. Corsano, A.R. Vecchietti and J.M. Montagna, Optimal design for sustainable bioethanol supply chain considering detailed plant performance model. *Comput. Chem. Eng.* **35** (2011) 1384–1398.

[7] G. Corsano, Y. Fumero and J.M. Montagna, Integrated decision making for the optimal bioethanol supply chain. *Energy Convers. Manage.* **88** (2014) 1127–1742.

[8] M.G. Doggar, M. Shahzad Khurram, S. Mirza, M. Ghauri, F. Jamil, N. Muhammad, S. Rafiq and M.H. Jaffery, Biomass power generation potential and utlization in pakistan. *Curr. Org. Chem.* **22** (2018) 1–16.

[9] J.R. Doyle and R.H. Green, Efficiency and cross-efficiency in DEA derivations, meanings and uses. *J. Oper. Res. Soc.* **45** (1994) 567–578.

[10] L.S. Ferreira and J.O. Trierweiler, Modeling and simulation of the polymeric nanocapsule formation process. *IFAC Proc. Vol.* **42** (2009) 405–410.

[11] V. Gonela, J. Zhang and A. Osmani, Stochastic optimization of sustainable industrial symbiosis based hybrid generation bioethanol supply chains. *Comput. Ind. Eng.* **87** (2015) 40–65.

[12] K. Grzesik and M. Malinowski, Life cycle assessment of mechanical–biological treatment of mixed municipal waste. *Environ. Eng. Sci.* **34** (2017) 207–220.

[13] Y. Gu and B.K. Wylie, Using satellite vegetation and compound topographic indices to map highly erodible cropland buffers for cellulosic biofuel crop developments in eastern Nebraska, USA. *Ecol. Indic.* **60** (2016) 64–70.

[14] R. Kesharwani, Z. Sun and C. Dagli, Biofuel supply chain optimal design considering economic, environmental, and societal aspects towards sustainability. *Int. J. Energy Res.* **42** (2018) 2169–2198.

[15] F. Mafakheri and F. Nasiri, Modeling of biomass-to-energy supply chain operations: applications, challenges and research directions. *Energy Policy* **67** (2014) 116–126.

[16] M. Marufuzzaman, S.D. Eksioglu, X. Li and J. Wang, Analyzing the impact of intermodal-related risk to the design and management of biofuel supply chain. *Transp. Res. Part E: Logistics Transp. Rev.* **69** (2014) 122–145.

[17] W.A. Marvin, L.D. Schmidt and P. Daoutidis, Biorefinery location and technology selection through supply chain optimization. *Ind. Eng. Chem. Res.* **52** (2012) 3192–3208.

[18] S. Mohseni and M.S. Pishvaee, A robust programming approach towards design and optimization of microalgae-based biofuel supply chain. *Comput. Ind. Eng.* **100** (2016) 58–71.

[19] S. Mohseni, M.S. Pishvaee and H. Sahebi, Robust design and planning of microalgae biomass-to-biodiesel supply chain: a case study in Iran. *Energy* **111** (2016) 736–755.

[20] M. Moulod, A. Jalali and R. Asmatulu, Biogas derived from municipal solid waste to generate electrical power through solid oxide fuel cells. *Int. J. Energy Res.* **40** (2016) 2091–2104.

[21] R.T. Ng and C.T. Maravelias, Design of cellulosic ethanol supply chains with regional depots. *Ind. Eng. Chem. Res.* **55** (2015) 3420–3432.

[22] A. Osmani and J. Zhang, Economic and environmental optimization of a large scale sustainable dual feedstock lignocellulosic-based bioethanol supply chain in a stochastic environment. *Appl. Energy* **114** (2014) 572–587.

[23] A. Osmani and J. Zhang, Multi-period stochastic optimization of a sustainable multi-feedstock second generation bioethanol supply chain – A logistic case study in Midwestern United States. *Land Use Policy.* **61** (2017) 420–450.

[24] M. Patel, X. Zhang and A. Kumar, Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: a review. *Renew. Sustainable Energy Rev.* **53** (2016) 1486–1499.

[25] S.R. Poudel, M. Marufuzzaman and L. Bian, Designing a reliable bio-fuel supply chain network considering link failure probabilities. *Comput. Ind. Eng.* **91** (2016) 85–99.

[26] S. Rafael, L. Tarelho, A. Monteiro, T. Monteiro, C. Gonçalves, S. Freitas and M. Lopes, Atmospheric emissions from forest biomass residues to energy supply chain: a case study in Portugal. *Environ. Eng. Sci.* **32** (2015) 505–515.

[27] G.J. Ruiz-Mercado, M.A. Gonzalez and R.L. Smith, Sustainability indicators for chemical processes: III. Biodiesel case study. *Ind. Eng. Chem. Res.* **52** (2013) 6747–6760.

[28] J. Sadhukhan and K.S. Ng, Economic and European union environmental sustainability criteria assesment of bio-oil-based biofuel systems: refinery integration cases. *Ind. Eng. Chem. Res.* **50** (2011) 6794–6808.

[29] H. Sahebi, S. Nickel and J. Ashayeri, Strategic and tactical mathematical programming models within the crude oil supply chain context – A review. *Comput. Chem. Eng.* **68** (2014) 56–77.

[30] N. Shabani, T. Sowlati, M. Ouhimmou and M. Rönnqvist, Tactical supply chain planning for a forest biomass power plant under supply uncertainty. *Energy* **78** (2014) 346–355.

[31] B. Sharma, R.G. Ingalls, C.L. Jones and A. Khanchi, Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. *Renew. Sustainable Energy Rev.* **24** (2013) 608–27.

[32] B. Sharma, R.G. Ingalls, C.L. Jones, R.L. Huhnke and A. Khanchi, Scenario optimization modeling approach for design and management of biomass-to-bio-refinery supply chain system. *Bioresour. Technol.* **150** (2013) 163–171.

[33] X. Wang, G. Huang, Z. Liu, and C. Dai, Hybrid inexact optimization approach with data envelopment analysis for environment management and planning in the city of Beijing, China. *Environ. Eng. Sci.* **29** (2012) 313–327.

[34] L. Wang, M. Sharifzadeh, R. Templer and R.J. Murphy, Bioethanol production from various waste papers: economic feasibility and sensitivity analysis. *Appl. Energy* **111** (2013) 1172–1782.

[35] F. Xie, Y. Huang and S. Eksioglu, Integrating multimodal transport into cellulosic biofuel supply chain design under feedstock seasonality with a case study based on California. *Bioresour. Technol.* **152** (2014) 15–23.

[36] H. Zhou, Y. Yang, Y. Chen and J. Zhu, Data envelopment analysis application in sustainability: the origins, development and future directions. *Eur. J. Oper. Res.* **264** (2018) 1–16.