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Bioethanol sustainable supply chain design: A multi-attribute bi-objective structure

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ABSTRACT

To design a bioethanol supply chain, along with the transportation and operational costs, it is vital to consider more factors categorized into three sustainability pillars (i.e. economy, social and environment). In this paper, to develop a mathematical model for bioethanol supply chain (BSC) , we propose a two-phase methodology; in the first phase, using a sustainable framework of attributes contributing to the facility location selection in the BSC network, we calculate the sustainability score of alternatives through employing the best-worst method (BWM). Then, considering the results of the multi-attribute step as the parameters of an objective function called the sustainability value function, we develop a bi-objective multi-level bioethanol supply chain model. To solve the proposed model, a Nested bi-objective Optimization Genetic Algorithm (NbOGA) is introduced in this research. Finally, we evaluate the performance of the presented BSC model and the algorithm for a real-world problem. The results show that using the proposed structure, both sustainability attributes and transportation costs are appropriately satisfied in the BSC network.

1. Introduction

The economic and population growth along with consequential industry development has culminated in increasing worldwide energy demand for residential, transportation, commercial and industrial sectors, especially in developing countries (Ghaderi et al., 2016). Reportedly, the dramatic rise of global energy and fuel consumption around the world not only diminishes the non-renewable energy sources in the foreseeable future (Shafiee & Topal, 2009), but also would exacerbate the environmental problems through escalated greenhouse gas (GHG) emission and intensive fossil fuel resource evacuation (Bahrampour et al., 2020). Accordingly, some researchers argue that the substitution of fossil fuels by renewable energy sources (such as wind, solar, geothermal, tidal and biomass) is the key to satisfy an important share of the world's energy demand and is fundamental to offer long-term sustainable eco-friendly power generation opportunities (Asif & Muneer, 2007). In this regard, biofuels which are derived from biomass resources, have attracted much attention as a promising and realizable alternative of the present commonly used fuels (Alonso et al., 2010; Dinh et al., 2009). Among different types of biofuels, bioethanol is being widely investigated as a valuable fuel source due to its potential to reduce GHG and relatively high energy yield (Dunnett et al., 2008; Jones et al., 1994).

In general, the biomass feedstock used for ethanol production is corn and corn stover (Ekşioğlu et al., 2009). As depicted in Fig. 1, the bioethanol supply chain (BSC) is a complex multi-level supply chain as it forms a combination of agricultural land and industrial sites including croplands, bio-refineries, disposal sites and distribution outlets. The challenge of achieving sustainability in such a cross-tier supply chain is extremely profound and has been proven to be eminently complicated when the social, environmental and economic dimensions are considered together in a circular resource framework (S. C. Koh et al., 2012; S. L. Koh et al., 2017). It may be the main reason for the scarcity of the evaluation of sustainable supply chains beyond the traditional tier-1 level, as investigated by a recent literature review (Martins & Pato, 2019).

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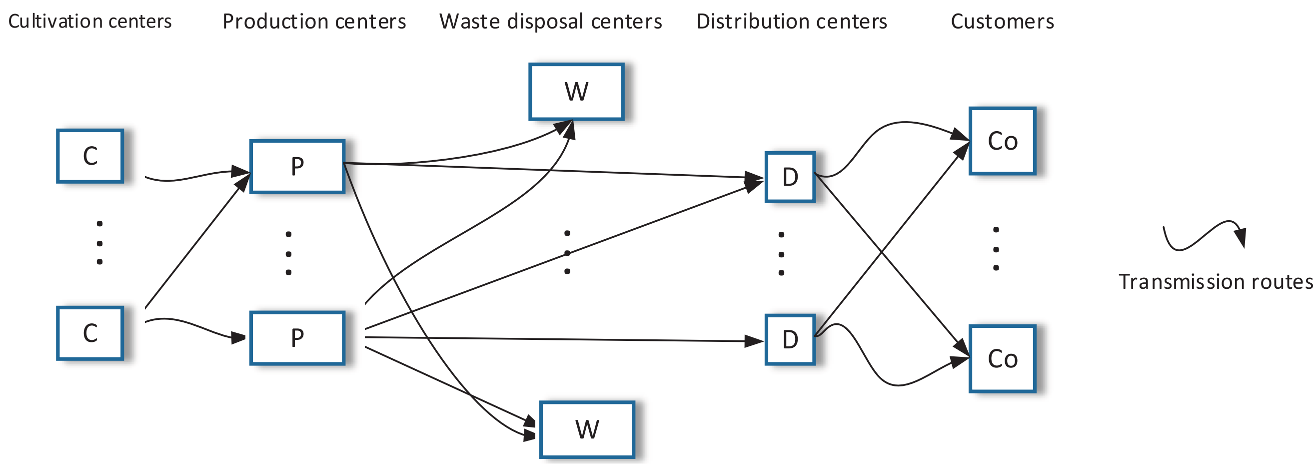

Fig. 1. The scheme of bioethanol production supply chain.

Clearly, finding the best location along with the optimal allocation of resources and production to the BSC entities, are of high importance in pursuing sustainability. Traditionally, mathematical models have widely been used to solve a vast array of supply chain management problems. However, sustainability provides greater challenges where problems have become more difficult to be mathematically modeled (Bai & Sarkis, 2018; Gonzalez et al., 2018). It has been demonstrated that it is practically difficult to develop mathematical models which can incorporate multiple levels of a networked supply chain, and thus significant simplifications in the simulation process should be considered. (Sarkis et al., 2019). Indeed, mathematical models documented in the literature do not cover all of the sustainability attributes which contribute to the bioethanol supply network design decision making process. This may have to do with the fact that an increase in the number of constraints and variables both complicates and impedes the feasibility of mathematical modelling (Kheybari et al., 2020). Hence, there is a need to develop new methods and tools to tackle the complexities that arise from real case scenarios.

It has been demonstrated that, in practice, developing mathematical models that can fully incorporate multiple levels of a networked supply chain is difficult, and thus there should be substantial simplifications made in the simulation process. In the first step, using the frameworks of economic, environmental and social attributes contributing to the location selection of cultivation lands, disposal sites, bioethanol production plants, and distribution centers, we calculate the sustainability indices of the alternatives in each level of the BSC by utilizing MADM approach. Accordingly, using the utilities found in the previous step as the parameters of an objective function – referred to as sustainability value function, a bi-objective mathematical model is developed which attempts to select the most sustainable locations in each tier of the BSC while trying to minimize the transportation cost. Finding the sustainability index of different locations for a given purpose through employing the MADM method is not new; however, the novelty of the presented methodology is the way it uses the utilities of the alternatives in the mathematical model to determine the best location of the nodes in the BSC network, which is rare in the existing literature.

To solve the presented model, we propose a customized multi-attribute bi-objective optimization algorithm as a second contribution of this paper. We utilize the independency among the variables and partition the search space into three independent subproblems; each with one objective. We solve each solution separately. Then, by combining the obtained sub-solutions, we find a complete solution for the main problem. To this end, we use a higher level bi-objective genetic algorithm which benefits a non-dominating ranking procedure. The performance of the proposed bi-objective model is validated by conducting a real-world case study in Iran, which is alarmingly challenged by economic, environmental and social problems. However, considering the prodigious biomass resources available in the country, Iran has the potential to supply 25% of its domestic gasoline demand. This, in turn, has heated the biofuel production issue up in Iran (Kheybari, Rezaie, et al., 2019).

The rest of this paper is structured as follows. In Section 2 by reviewing the relevant works, we identify research gaps. To design the bioethanol supply chain network, we formulate a mathematical model in section 3. In Section 4, we introduce a new metaheuristic algorithm to solve the proposed model. We describe the data collection process in Section 5. The proposed model is solved and analyzed in Section 6, and the conclusion and suggestions for future research are presented in Section 7.

2. Literature review

Although numerous pieces of research have been discretely conducted to find the best location of entities in each level of the BSC (i.e. farmlands, bioethanol production plants, disposal sites and distribution centers), to review the most relevant research to the present work, we only discuss the papers that are related to bio-refinery location selection or biofuel supply chain design, with a special focus on bioethanol.

In almost all of the research surveyed, economic sustainability has been considered as the primary criterion; reportedly, the mathematical models in approximately half of these papers have just focused on cost minimization or profit maximization and ignored the other sustainability pillars. For instance, Lopez et al. (López et al., 2008) conducted a study to find the best location for a biomass power generation plant in Spain using particle swarm optimization (PSO). The objective function of this work is to maximize the profitability index, which is defined as the net worth of benefits from the sale of electricity minus the operation, maintenance, and transportation costs, as well as initial investment. The results of their study demonstrated that the technical limitations and voltage regulations are of great importance in biomass power generation systems. In Chinese and Meneghetti (2009) a configuration of a wood-fired biofuel power plant is suggested using a mixed-integer programming (MIP) model, developed to minimize total supply chain costs. In that study, the author chose the biomass circulation level in the supply network along with the utilization level of the processing equipment, as decision variables. Eksioglu et al., (2009) proposed a MIP model to design the supply chain of biorefineries as well as analyze the logistical challenges of supplying biomass to a biorefinery. The presented model is supposed to minimize the total harvesting, inventory, production, and transportation costs by determining the optimal level of number, size and location of biorefineries as well as the amount of biomass shipped, inventorized and processed during a given time period. The biorefinery considered in that work, uses lignocellulosic biomass to produce cellulosic ethanol (c-ethanol). Using the data obtained from Mississippi state, the authors showed that the transportation costs, accessibility to biomass feedstock, type of technology,y and harvesting and collection costs are important factors in supply chain design decisions.

Difs et al. (2010) analyzed different scenarios of the biomass gasification process with the aim of maximizing annual profits (revenue from energy sales minus investment, fuel, and maintenance costs). For this purpose, they formulated a MIP model with the new investment capacity and the type of investment for the future, as the decision variables. The size, location and supply centers of different power plants in Spain were discovered by Vera et al. (2010); the remnants of olive tree pruning and the turbine gasification, are considered as the biomass feedstock and the technology used in this work, respectively. The researchers made use of GIS data to identify the location and number of olive trees per square kilometer, roads, and neighborhoods with power lines. The decision variables used in their study are the choice of biomass supply location and the quality of biomass prepared from the suppliers to each power plant. The size and the location of the power plants are determined using *meta*-heuristic algorithms such as genetic algorithm, PSO and Bees algorithm.

To optimize the supply chain of a 230 MW biomass power plant in Canada which is fed by two types of biomass, namely wood harvesting residues and unused biomass (such as trees damaged by fire), Alam et al. (2012) proposed a dynamic nonlinear programming model based on geographic information systems. The objective function of their presented model was to minimize the total cultivation and transportation cost of the biofuel supply chain. The decision variables in their study are the harvest level of each type of biomass per month. Similarly, to maximize the overall value of a biomass supply chain in Canada, Shabani and Sowlati (2013) proposed a MIP model which considers biomass production and storage, energy production and ash management in an integrated framework. The suggested model is then solved using an external approximation algorithm in the AIMMS software package. The optimal solution offers more profit than the real case profit of the power plant. The results demonstrate that investing in a new ash recovery system provides economic benefit for the power plant and environmental benefits, as well.

Duarte et al. (2014) proposed a MIP to locate a bioethanol power plant in Colombia. The objective function of the model presented in their study is profit maximization. They showed that the selected locations are mainly affected by transportation costs and the availability of raw materials, and also the *access to raw material* is one of the most important factors which influence the production capacity. An optimization framework for designing a biorefinery system considering the required water and wastewater discharge is presented in (López-Díaz et al., 2017). This optimization approach was used to select raw materials, cultivation sites and processing facilities and conversion technologies. Similar to all of the above-mentioned works, the objective function of their research is the maximization of profit. They applied their proposed approach in Mexico, the results of which demonstrated that by optimizing water usage and wastewater discharge, many economic benefits are obtained.

Contrary to the research introduced so far, there are some works in which the environmental and social dimensions are considered along with the economic factors. The research which are conducted on designing a biofuel supply chain works with more than one (economic) objective function, should be considered significantly important as to optimize the supply chain of a power plant, it is necessary to formulate the problem with more than one objective (M. B. Alam et al., 2009). Santibañez-Aguilar et al. (2014) developed a multi-period multi-objective MIP model to optimize the supply chain of biorefinery. The objective functions of their proposed model are set to maximize supply chain profits, minimize environmental impacts, and maximize the number of jobs created. To demonstrate the applicability of the model, a case study was conducted to meet the demand for ethanol and biodiesel in Mexico. The results showed that the number of jobs created by the implementation of the biorefinery supply chain plan has significant social effects. Moreover, Delivand et al. (2015) conducted a study on the optimal location of biopower plants in Italy. They used an integrated approach based on GIS and multi-attribute analysis for the logistics of biomass conversion into electricity in a region of Italy. For this purpose, a number of suitable places were first identified according to a set of criteria; then, the optimal locations were selected according to the transportation costs and the accessibility of biomass, with the aim of minimizing the logistics costs and the amount of greenhouse gas emissions. Roni et al. (2017) proposed a MIP model for the design and management of a biofuel supply chain in the U.S. Minimizing transportation costs, minimizing greenhouse gas emission with respect to transportation-related activities, and maximizing social benefits (the number of local jobs created) are the objectives of their model, which was examined using real case data. The authors made use of numerical analysis to estimate the amount and the cost of cellulosic ethanol distributed under different production conditions.

An integrated multi-objective mathematical framework is presented in (Petridis et al., 2018) to model production, transportation and warehousing of biomass products derived from forests and energy crops. The authors formulated a MIP model applied to all possible weight representations under environmental, economic and social attributes. Aiming to reduce the CO_2 gas emission and the total cost, while trying to maximize the GDP through warehouse installation, the authors conducted a trade-off among the attributes categorized in the sustainability pillars. The authors demonstrated that the economic and environmental aspects seem to move in the same direction but opposite to the social criterion. Khoo et al. (2019), proposed an integrated model combining Life Cycle Assessment (LCA), SC-risk factors and GIS to analyze the value chain of a bio-derived chemical product. Contrary to most of the similar research, the hybrid method presented in their research investigates the environmental and economic aspects of the BSC from farm to final product distribution and sales. In this vein, using different sustainability metrics including *total cost*, *global warming potential*, *acidification potential, eutrophication potential* and *land footprint*, they assessed 8 distinctive scenarios in both qualitative and quantitative form.

Reviewing existing literature reveals the following gaps.

- Previous researches have failed to suggest a holistic approach which pays attention to the entire BSC (i.e. the logistics associated with different levels of the BSC including feedstock production, feedstock inventory management, transportation, biofuel production and distribution), and have focused on a specific part of the BSC, when the goal is to select the best location for biorefineries. However, considering all of the single-level collaborations between the tiers of the BSC, would culminate in making more deliberate strategic decisions which in turn, results in lower transportation and material costs and reduced capital asset investment.
- Almost all of the previous works have chosen only a handful of the attributes categorized into economic, environmental and social dimensions in their models which would call the compatibility of those models with real-world problems, into question. Nonetheless, needless to mention that the greater the number of attributes, the more realistic the simulated problem.

To fill these gaps, we designed a sustainable multi-level bioethanol supply chain that incorporates biomass cultivation lands, disposal sites, bioethanol production plants and distribution nodes. In each level of the proposed BSC model, a comprehensive set of attributes contributing to sustainable location selection is employed, which is rare in the literature. To the best of our knowledge, the work of Khoo et al. (2019) is the only study that takes an integrated view of a bio-derived product supply chain from the perspective of sustainability; however, the structure of the supply chain offered by Khoo et al. is totally different from the BSC proposed in our work.

3. Problem formulation

Considering a set of alternatives for each level of the supply chain of bioethanol production (see Fig. 1) and using both the criteria contributing to the location selection problem in the BSC from the different dimensions of sustainability (including economic, social and environment aspects(, and the transportation cost between the nodes of the network, designing a supply chain mathematical model for bioethanol is the problem that we want to formulate and solve. According to the demand and the production capacity of each facility, the model must be able to select more than one place in each level. It is worth noting that, to decrease the size of the mathematical model and to take advantage of experts' opinions, we make use of the result of the MADM to calculate the sustainability index of candidate places and employ these utilities in the proposed model as the parameters of the so-called "sustainability value function".

3.1. Assumptions and notations

To formulate the bioethanol supply chain network, the following assumptions and notations are considered:

Assumptions

- The mode of transport is road (i.e. truck).
- The centers located at different levels of the BSC have capacity restrictions.
- The transportation cost of raw materials and products is a linear function of distance.
- The demand of different nodes is known.
- Demand is way less than the sum of distribution centers' capacity.

Notations

Indices	
I	Set of candidate places for corn cultivation ($i \in I$)
K	Set of candidate places for bioethanol production ($k \in K$)
M	Set of candidate places for waste disposal ($m \in M$)
H	Set of candidate places for distribution centers of bioethanol ($h \in H$)
D	Set of the demand node ($d \in D$)
Parameters	
U^C_i	Sustainability performance of biomass (corn) cultivation place i
U^P_k	Sustainability performance of candidate bioethanol production place k
U^W_m	Sustainability performance of candidate waste disposal place m
U^D_d	Sustainability performance of candidate bioethanol distribution place m
C^C_{ik}	Transportation cost of corn from node i to k
C^P_{kh}	Transportation cost of bioethanol from node k to h
C^W_{km}	Transportation cost of waste disposal from node k to m
C^D_{hd}	Transportation cost of bioethanol from node h to d
V^C_i	Maximum cultivation capacity of node i
α	Yield per kilogram of corn in bioethanol production
Pc_k	Maximum production capacity of node k
N_d	Demand of node d
Wc_m	Maximum waste disposal capacity of node m
N^C	Number of corn cultivation areas
N^P	Number of bioethanol production places
N^W	Number of waste disposal places
N^D	Number of distribution centers
V^T_h	Maximum distribution capacity of node h
V^C_{max}	Capacity of a truck to transport corn
V_{max}	Capacity of a truck to transport bioethanol
V^W_{max}	Capacity of a truck to transport waste disposal
C^{TC}_i	Average cost of truck rental in center i
C^{TP}_k	Average cost of truck rental in center k
C^{TD}_h	Average cost of truck rental in center h
Variables	
x_{ik}	Biomass (i.e. corn) transferred from node i to k
l_{kh}	Bioethanol transferred from node k to h
R_{km}	Waste disposal transferred from node k to m
D_{hd}	Bioethanol transferred from node h to d
y^C_i	Binary variable, 1 if the place i is selected for biomass cultivation, 0 otherwise
y^P_k	Binary variable, 1 if the place k is selected for bioethanol production, 0 otherwise
y^W_m	Binary variable, 1 if the place m is selected for waste disposal, 0 otherwise
y^D_h	Binary variable, 1 if the place h is selected for distribution center, 0 otherwise

(*continued on next column*)

(*continued*)

3.2. Objective functions

We consider two objective functions for the mathematical model as follows. The first objective function (Equation (1) assures the selection of the places with the best performance from the sustainability approach, as suitable locations for each of the four sections of the bioethanol supply chain network. To calculate the sustainability score of candidate places (i.e. $U^C_i, U^P_k, U^W_m \text{and} U^D_d$), which will be elaborated upon later, we apply the result of MADM as the parameters of the objective function.

$$\max F_1 = \sum_i \sum_k U^C_i x_{ik} + \sum_k \sum_h U^P_k l_{kh} + \sum_k \sum_m R_{km} U^W_m + \sum_h \sum_d U^D_d D_{hd} \tag{1}$$

The second objective function (Equation (2) minimizes the total transportation costs. As indicated in Equation (2), this objective function has two terms, one of which describes the rent cost and the other guarantees the selection of the shortest distance between the two specified nodes in the bioethanol supply chain network.

$$\begin{aligned} minF_2 = & \sum_i \sum_k \left(C^C_{ik} x_{ik} + C^{TC}_i \left\lceil \frac{x_{ik}}{V^C_{max}} \right\rceil \right) + \sum_k \sum_h \left(C^P_{kh} l_{kh} + C^{TP}_k \left\lceil \frac{l_{kh}}{V^P_{max}} \right\rceil \right) \\ & + \sum_k \sum_m \left(C^W_{km} R_{km} + C^{TP}_k \left\lceil \frac{R_{km}}{V^W_{max}} \right\rceil \right) + \sum_h \sum_d \left(C^D_{hd} D_{hd} + C^{TD}_h \left\lceil \frac{D_{hd}}{V^D_{max}} \right\rceil \right) \end{aligned} \tag{2}$$

3.3. Constraints

To design the bioethanol supply chain network, we applied four types of constraints to the mathematical model as follows.

Network constraints: Considering the two objective functions, Equations (3) to (5) guarantee the flow of raw material and product between the nodes of the BSC. To be more precise, as indicated in Equation (3), α percent of the biomass (i.e. corn) is converted to bioethanol and transported to distribution centers and according to Equation (4) the rest of the biomass (i.e. $(1-\alpha)$ percent) is disposed as waste and transported to the disposal sites. The flow of bioethanol between the production and distribution centers is formulated in Equation (5). The reason Equation (5) is not an equality constraint is due to the possibility of keeping inventory at the distribution hubs.

$$\sum_i \alpha(x_{ik}) = \sum_h l_{kh} \quad \text{For all } k \tag{3}$$

$$\sum_i (1-\alpha) x_{ik} = \sum_m R_{km} \quad \text{For all } k \tag{4}$$

$$\sum_k l_{kh} \geq \sum_d D_{hd} \quad \text{For all } h \tag{5}$$

Capacity of centers: Equations (6) to (9) take into account the maximum capacity in farmlands, production centers, waste disposal sites, and distribution centers in the BSC network, respectively.

$$\sum_k x_{ik} \leq V^C_i y^C_i \quad \text{For all } i \tag{6}$$

$$\sum_i x_{ik} \leq Pc_k y^P_k \quad \text{For all } k \tag{7}$$

$$\sum_k R_{km} \leq Wc_m y^W_m \quad \text{For all } m \tag{8}$$

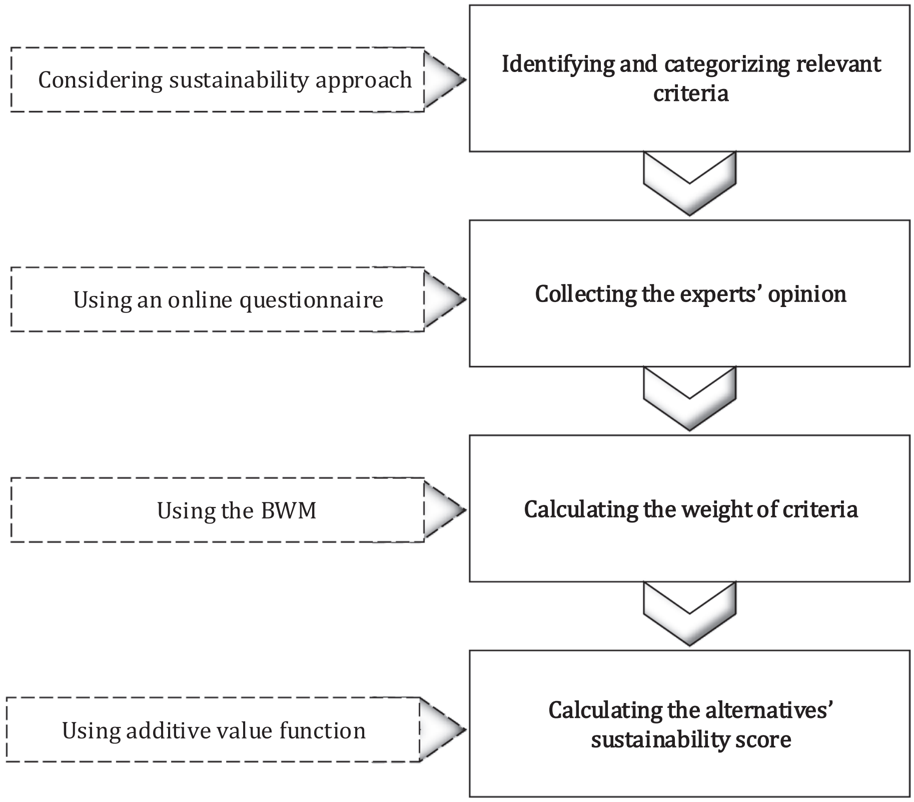

Fig. 2. The steps of calculating the sustainability index of candidate places.

$$\sum_k l_{kh} \leq V_h^T y_h^D \quad \text{For all } h \tag{9}$$

Number of facilities: The maximum allowable number of cultivation, production, distribution, and waste disposal locations are indicated in Equations (10) to (13), respectively.

$$\sum_i y_i^C \leq N^C \tag{10}$$

$$\sum_K y_k^P \leq N^P \tag{11}$$

$$\sum_m y_m^W \leq N^W \tag{12}$$

$$\sum_h y_h^D \leq N^D \tag{13}$$

Demand satisfaction: Equation (14) assures the assumption that the demands should be completely satisfied.

$$\sum_h D_{hd} = N_d \quad \text{For all } d \tag{14}$$

3.4. Sustainability value of centers

As mentioned earlier, to calculate the sustainability indices of alternatives (i.e. provinces of Iran) as the parameter of the first objective function, the MADM approach proposed by Kheybari et al. (2019) is employed in this research. The process involves four steps presented in Fig. 2. First, reviewing the relevant literature, we identify and categorize the location selection attributes for the cultivation, distribution, and waste disposal centers (see Fig. 3).

To categorize the attributes, the sustainability approach is applied in this research. To this end (Kheybari et al., 2021; Kheybari & Rezaie, 2020; Salamirad et al., 2023):

- All the attributes that lead to environmental hazards/ benefits are categorized into an environmental dimension
- Attributes related to people, rules and regulations and government are categorized as social factors.
- Attributes lead to economic gains/losses categorized into economic dimensions.

Please note that the letters D, C, and W next to each criterion in Fig. 3 indicate the factors contributing to the sustainability performance of cultivation, distribution, and waste disposal locations, respectively. In the next step, we collected the opinion of relevant experts to compute the weight of attributes. Having the experts' opinions in hand, in the next step, using the best-worst method (BWM) (Rezaei, 2015), we determined the weight of attributes. Note that we describe the steps of the BWM in the Appendix. Finally, in the last step, we calculated the sustainability index of the provinces of Iran with the additive value function (Equation 15).

$$V_i = \sum_j w_j u_{ij} \quad \text{For all } i \tag{15}$$

where w_j is the weight of attribute j and u_{ij} is the normalized score of province i in criterion j. We used Equations 16 and 17 to compute the normalized score of candidate location for positive and negative attributes in this research, respectively.

$$u_{ij} = \frac{z_{ij}}{\sum_i z_{ij}} \quad \text{For all } i \text{ and } j \tag{16}$$

$$u_{ij} = \frac{1/z_{ij}}{\sum_i 1/z_{ij}} \quad \text{For all } i \text{ and } j \tag{17}$$

where z_{ij} is the performance of province i with respect to attribute j. It is worth mentioning that we used the results obtained by Kheybari et al. (Kheybari, Kazemi, et al., 2019) as the sustainability index of the production places in the mathematical model.

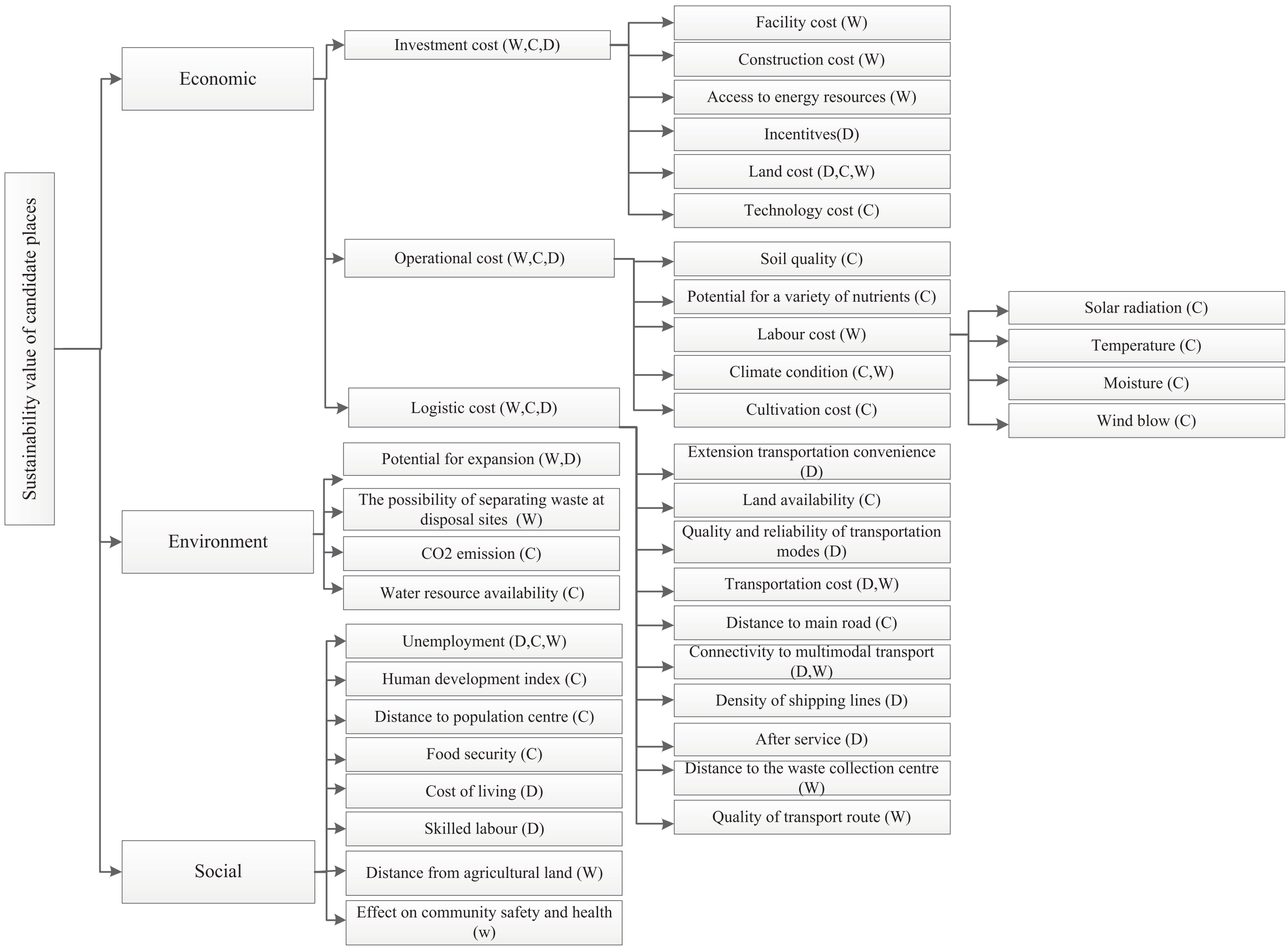

Fig. 3. The hierarchy structure of attributes contributing to the sustainability performance of cultivation, distribution, and waste disposal locations.

4. Nested bi-objective optimization genetic algorithm (NbOGA)

Since the BSC problem is a general case of allocation problem which is an NP-hard problem, there is no polynomial-time algorithm to solve it (Farahani et al., 2010). We present a customized evolutionary approach called *nested bi-objective optimization genetic algorithm* (NbOGA).

The multi-objective optimization algorithms follow two main goals, the first goal is finding a set of feasible solutions called *non-dominated solutions* which are as close as possible to the *Pareto optimal solutions*, and the second goal is finding a set of diverse non-dominated solutions which are candidates of the entire objective space. A solution s is called a *non-dominated solution* if there is no solution s' such that is not worse than s in all objectives, and there is at least one objective in which s' is preferred to s. The *Pareto optimal solutions* are the non-dominated solutions of the whole search space of a problem (Coello et al., 2007; Deb, 2001).

Evolutionary algorithms start with a random set of solutions, called *population*, and iteratively evolve it by making a balance between *exploring* and *exploiting*. They use three main operators *selection*, *crossover* and *mutation*. The selection operator tries to increase the average fitness of the population by choosing a set of high-fitness solutions. This is called *exploitation*. Several selection operators have been introduced such as Tournament and roulette wheel (Coello et al., 2007). The crossover operator tries to reach *exploring*. That is, increases the diversity of the population by keeping the average fitness of the population. Single-point and linear combinations are two popular crossover operators (Deb, 2001). The last operator which is mutation helps to improve the exploring power by randomly changing some features of a solution. This may discover new parts of the search space. So, it prevents *premature convergence* of the population and consequently helps to find the global optimum.

A complete solution for the BSC problem is the decision variables x_{ik}, l_{kh}, R_{km}, D_{hd} and the binary variables y_i^C, y_k^P y_m^W and y_h^D for all possible indices i, k, h and m. So, a traditional evolutionary algorithm considers these four reals and four binary variables as a chromosome in the algorithm. For an instance of the problem with $NC = NP = NW = ND = 30$, the size of its corresponding chromosome is 3720 which yields a very high dimensional search space. On the other hand, the problem contains some hard constraints, Constraints (3), (4) and (14). This is a very difficult search problem. To overcome these difficulties, we propose a nested evolutionary approach that utilizes three nested single-objective genetic algorithms to reduce the dimension of the search space.

Before explaining the details of the proposed algorithm, let describe the idea. Each solution to the problem contains the variables x_{ik}, R_{km}, l_{kh}, D_{hd}, y_i^C, y_k^P, y_m^W and y_h^D for all possible indices i, k, h and m. Fortunately, this optimization problem can be divided into three independent optimization sub-problems:

- **Sub-problem (*i*):** The optimization sub-problem with variables x_{ik}, y_i^C and y_k^P, and Constraints (6), (7), (10) and (11).
- **Sub-problem (*ii*):** The optimization sub-problem with variables R_{km} and y_m^W, and Constraints (8), and (12).

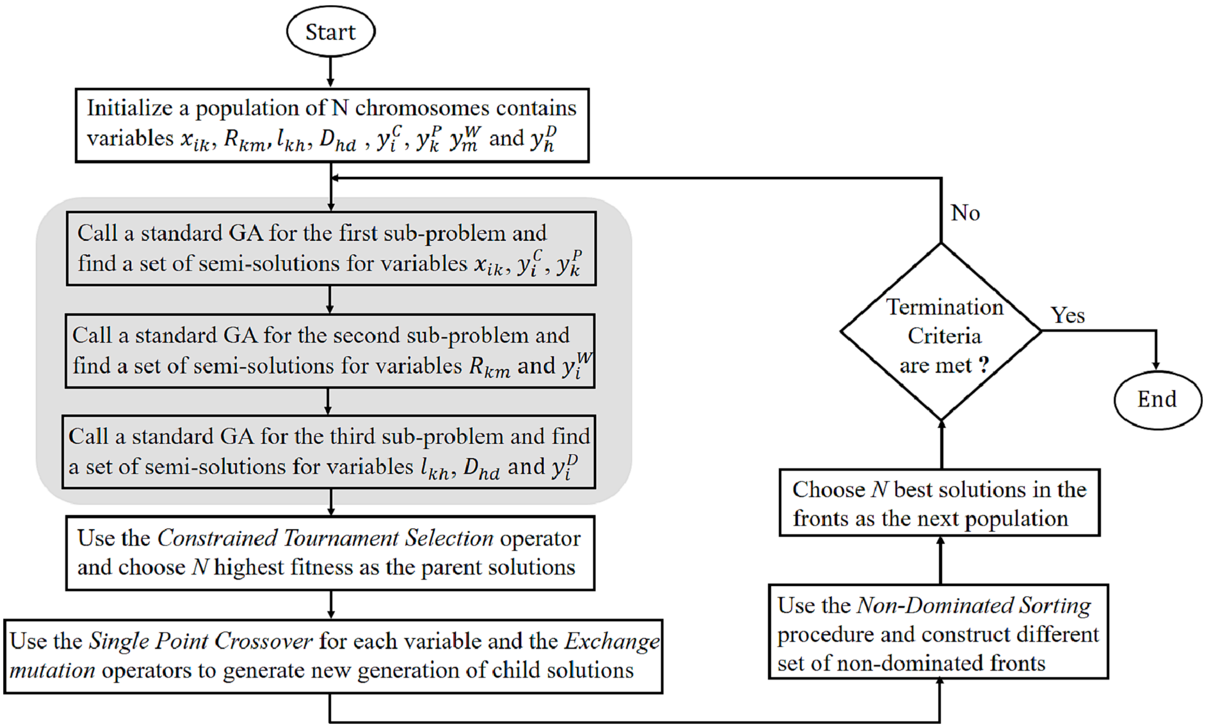

Fig. 4. Flowchart of NbOGA. The highlighted part is the running of three independent single-objective genetic algorithms. The result of this part is a complete solution to the BSC problem. The other parts implement a bi-objective genetic algorithm.

- **Sub-problem (*iii*):** The optimization sub-problem with variables l_{kh}, D_{hd} and y_h^D, and Constraints (5), (9), (13) and (14).

The connection between the first and second sub-problem is Constraint (4), and the connection between the first and the third sub-problems is Constraint (3). Fortunately, there is no connection between the second and the third sub-problems, so, there is no need to consider whole the search space together. On the other hand, if a solution for the first sub-problem is available, we can use the hard connection Constraint (4) to find some solutions for the variables R_{km} and y_m^W. That is, using the determined values of x_{ik} and a random simple step the values of R_{km} is generated such that satisfy the constraint $\sum_i(1-\alpha)x_{ik} = \sum_m R_{km}$ for all k. Independently Constraint (3) as a hard constrain is used to generate the values of l_{kh} and consequently solving the third optimization sub-problem. It is notable that in all of these sub-problems, the fitness function is to minimize the constraint violation, called minimizing the *penalty function* in the literature (Davoodi et al., 2015).

After running the above three genetic algorithms and solving the sub-problems and finding a complete solution for the BSC problem, the selection, crossover and mutation operators have been applied to progress the main bi-objective genetic algorithm with the objectives F_1 and F_2. Note that, for an instance of the problem with $NC = NP = NW = ND = 30$, the dimension of the search space for the first, second and third sub-problems is 960, 930 and 1830. Fig. 4 shows the flowchart of the proposed algorithm.

NbOGA considers a complete solution or chromosome contains variables x_{ik}, l_{kh}, R_{km}, D_{hd}, y_i^C, y_k^P y_m^W and y_h^D for the problem, however, it generates the solution in three heuristic steps. First, NbOGA randomly initializes a genetic population containing the variables x_{ik}, y_i^C and $y_k^{C'}$ for all possible i and k. It satisfies Constraints (10) and (11) in the initialization step. This means it just chooses at most NP centers as y_i^C to biomass cultivation and at most NC centers as $y_k^{C'}$ to bioethanol production. Then it uses a standard single-objective genetic algorithm to satisfy Constraints (6) and (7). The fitness objective is minimizing the constraint violation. Let call them *semi-solutions*. After finding a set of solutions that satisfy Constraints (6), (7), (10) and (11), NbOGA generates several copies of each semi-solutions using hard Constraint (4). It utilizes random steps but always satisfies this constraint. In this step the value of R_{km} are determined for all possible k and m. Then it uses another standard genetic algorithm to find solutions with minimum constraint violation of Constraint (8). In this step, it always satisfies Constraint (12), choosing at most NR centers for waste disposal. Similar to this step, the assignment of the variable l_{kh} is performed using randomly satisfying Constraint (3) and Constraint (13). There is a dependency between variables l_{kh} and D_{hd} with limit Constraint (14) which is $\sum_h D_{hd} = N_d$ for all d. This is also a hard constraint. Consequently, NbOGA randomly assigns the variable D_{hd} such that it satisfies this constraint implicitly. Therefore, Constraints (3) for l_{kh} and Equation (14) for D_{hd} are two randomly assignment procedures whose difficulty is simultaneously satisfying Constraints (5) and (9). This step is also performed by a single genetic algorithm with the objective of minimizing the penalty function.

After constructing a complete solution using the three-independent single-objective genetic algorithms, the main step of NbOGA runs to maximize F_1 and minimize F_2. To this end, first, the objective value and constraint violation of each child solution are computed. Then, using the constrained tournament selection operator, single-point crossover and exchange mutation operators, the population of children is reproduced. The constrained tournament selection operator randomly selects two solutions and introduces their winner as a parent to reproduce the child population. Between the two solutions s and s', the winner is determined based on the following rules:

- If both s and s' are infeasible, the winner is the solution with a minimum constraint violation.
- If either of s and s' is feasible, the winner is the feasible solution.
- If both s and s' are feasible, the winner is the solution that dominates the other one. If they are non-dominated, choose the solution whose distance from its neighbor is greater than that of the other one.

The constraint tournament selection operator first emphasizes

Table 1
Experts' information.

Centers	Experts				Average years of work experience
	Academic scholars (Ph.D.)	Ministry of Agriculture	Municipalities	Ministry of petroleum	
Biomass cultivation	18	12	0	0	18.4
Waste disposal	12	0	15	0	9.5
Distribution	7	0	0	8	7.5

Table 2
Sustainability performance of provinces of Iran for the four centers.

Provinces	U_i^C	U_k^P	U_m^W	U_d^D
Eastern Azarbaijan	0.029	0.034	0.024	0.028
Western Azarbaijan	0.032	0.029	0.027	0.025
Ardabil	0.030	0.034	0.243	0.030
Isfahan	0.027	0.029	0.028	0.031
Alborz	0.031	0.024	0.030	0.023
Ilam	0.032	0.037	0.042	**0.067**
Bushehr	0.039	0.030	0.065	0.032
Tehran	0.021	0.045	0.035	0.056
Chaharmahal and Bakhtiari	0.029	0.030	0.030	0.035
Southern Khorasan	0.033	0.035	0.040	0.040
Razavi Khorasan	0.033	0.036	0.026	0.036
Northern Khorasan	0.034	0.029	0.027	0.034
Khuzestan	0.034	**0.048**	0.038	0.048
Zanjan	0.035	0.035	0.021	0.027
Semnan	0.031	0.031	0.037	0.035
Sistan and Baluchestan	0.032	0.029	0.042	0.030
Fars	0.038	0.032	0.037	0.032
Qazvin	0.029	0.032	0.033	0.025
Qom	0.020	0.040	0.322	0.026
Kordestan	**0.041**	0.036	0.021	0.029
Kerman	0.038	0.026	0.034	0.027
Kermanshah	0.035	0.031	0.023	0.034
Kohgeluyeh and Boyer-Ahmad	0.037	0.032	0.027	0.048
Golestan	0.033	0.037	0.022	0.031
Gilan	0.035	0.032	0.019	0.026
Lorestan	0.039	0.029	0.020	0.030
Mazandaran	0.037	0.028	0.020	0.025
Markazi	0.029	0.031	0.022	0.023
Hormozgan	0.040	0.037	**0.072**	0.026
Hamadan	0.031	0.031	0.022	0.025
Yazd	0.034	0.026	0.071	0.029

finding feasible solutions. If both solutions are feasible, it emphasizes the first goal of multi-objective optimization, finding Pareto optimal solutions. So, it chooses the solution which dominates the other one as the winner. Finally, if none of the solutions dominates the other one, it emphasizes the second goal of multi-objective optimization, finding diverse solutions. So, it chooses the winner as the solution with a greater distance from its neighbors. This helps to preserve unique solutions in the population. Single-point crossover combines two solutions with a random cut in the chromosome. It generates two child solutions using two parent solutions by combining the first part of one parent with the second part of the other parent and vice versa. We use this for the binary variables and use random linear combinations of the parents for the real variables. The exchange mutation changes the position of two bits 0 and 1 for the binary variables.

In the last step of NbOGA, it combines the child and the parent population and constructs different non-domination fronts of the solutions using a non-dominated sorting procedure. To sort the solutions, NbOGA applies the Non-dominated Sorting Procedure explained in NSGA-II (Deb et al. 2002).

This procedure works based on the ranking of non-dominated solutions. It first checks the number of feasible solutions in the unified population with size $2N$. If it is less than N, the procedure easily selects N solutions with the minimum constraint violation. Otherwise, it constructs different fronts of non-dominated solutions in Step 3.2. It finds the non-dominated solutions of the population and calls them as $\mathrm{front}(1)$. Then, it puts aside $\mathrm{front}(1)$ and iteratively finds $\mathrm{front}(2)$. By repeating this, other frons of the non-dominated solution can be found. This step can be determined as soon as the number of solutions on the fronts is more than N. However, the solutions at the last selected front are chosen based on the second goal of multi-objective optimization which is providing diverse solutions. This is performed in Step 3.6 by choosing solutions whose distance from their neighbors is greater than the other solutions. This procedure runs in $O(N\log N)$ time using a sweep line or divide and conquer approach (Jensen, 2003). The termination condition of NbOGA is simply defined as a maximum iteration.

5. Data collection

According to the approach proposed in this paper, along with the data employed to solve the mathematical model, we need to collect the experts' opinions to calculate the sustainability performance of candidate places in different layers of the BSC network. To this end, we used an online questionnaire to collect the opinion of experts. The experts are chosen according to their working and LinkedIn profiles based on the relevant types of expertise needed for the weighting process. We summarized the information of the experts who contributed to this research in Table 1.

To collect information regarding the performance of Iranian provinces in each of the attributes (z_{ij}), and also to determine the parameters of the proposed mathematical model, we used the websites of the Statistical Center of Iran, the Law Enforcement Force of Iran, the Ministry of Health and Medical Education, the Institute for Research and Planning in Higher Education, the Ministry of Housing and Urban Development, the Ministry of Culture, the Ministry of Science, Research and Technology, the Ministry of Petroleum, and Iran Meteorological Organization. Using the BWM, we first compute the weight of the attributes presented in Fig. 3 and then, the sustainability performance of the alternatives in each level of the BSC is computed (Equation 15).

6. Results

Considering the weight of attributes presented in Fig. 3, and the additive value function (Equation 15) we calculate the sustainability score of Iran's provinces as candidate alternatives for the facilities presented in BSC network (see Table 2). After conducting MADM analysis on our data, it turned out that Kordestan, Khuzestan, Hormozgan and Ilam are the most appropriate places for corn cultivation, bioethanol

Table 3
Results of the two objective functions.

Non-dominated solutions	Total sustainability value ($\times 10^7$)	Total transportation costs (in trillion dollar)
Sol. 1	4.17	4.07
Sol. 2	4.65	4.45
Sol. 3	**4.70**	4.65
Sol. 4	4.55	4.41
Sol. 5	4.34	4.22
Sol. 6	4.46	4.35
Sol. 7	4.29	4.16
Sol. 8	4.58	4.46
Sol. 9	4.36	4.26
Sol. 10	4.16	**4.02**

production, establishing disposal sites, and distribution centers, respectively (see Table 2).

Nevertheless, choosing the best alternatives identified through the MADM step would not necessarily culminate in having an efficient BSC; as in this type of selection, we have taken the transportation costs of the materials, finished products and wastage for granted. To find an appropriate setting of the entities in each tier of the BSC, which not only guarantees a good performance on economic, environmental and social attributes but also ensures the least possible transportation cost, we decided to make use of a multi-objective mathematical model in which the utilities obtained from the MADM step are used as the parameters of the first objective function and the transportation cost between the nodes in different tiers of the BSC are considered in the second objective function. Reportedly, almost all of the similar researches have been focused on finding the best facility location and the optimal material flow in a biofuel supply chain; nevertheless, considering a set of sustainability attributes (Equation (1) along with the transportation costs (Equation (2) is rare in the literature. Identifying the best locations for cultivation, production, distribution, and waste disposal centers as well as raw material, product and waste flow between the selected locations are the outputs of the proposed model.

Considering the results of the MADM part presented in Table 2, we evaluate the multi-attribute bi-objective model for $N^C = N^P = N^W = N^D \leq 5$. We summarize the other parameters of this example in Tables A and B in the Appendix. As presented in Table 3, although we get many solutions from the algorithm, here we present a diverse set of 10 solutions from the Pareto optimal front. Among ten non-dominated solutions, Sol.3 has the highest value of F_1 and the least value of F_2 belongs to Sol.10 (see Table 3).

As shown in the Table 4, while the chosen places for cultivation lands

Table 4
The chosen provinces for different levels of BSC in all of the solutions.

Sol	Variable	Province	Variable	Province	Variable	Province	Variable	Province
1	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_9^W	Chaharmahal and Bakhtiari	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_{14}^W	Zanjan	y_6^D	Ilam
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{21}^W	Kermanshah	y_{26}^D	Lorestan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{22}^W	Kermanshah	y_{28}^D	Markazi
2	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_6^D	Alborz
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_6^D	Ilam
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_{14}^W	Zanjan	y_{10}^D	South Khorasan
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{21}^W	Kermanshah	y_{15}^D	Semnan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{22}^W	Kermanshah	y_{28}^D	Markazi
3	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_6^D	Ilam
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_{14}^W	Zanjan	y_9^D	Chaharmahal and Bakhtiari
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{21}^W	Kermanshah	y_{10}^D	South Khorasan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{22}^W	Kermanshah	y_{28}^D	Markazi
4	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_9^W	Chaharmahal and Bakhtiari	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_{14}^W	Zanjan	y_6^D	Ilam
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{21}^W	Kermanshah	y_{15}^D	Semnan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{22}^W	Kermanshah	y_{28}^D	Markazi
5	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_9^W	Chaharmahal and Bakhtiari	y_6^D	Ilam
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{14}^W	Zanjan	y_9^D	Chaharmahal and Bakhtiari
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{21}^W	Kermanshah	y_{26}^D	Markazi
6	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_9^W	Chaharmahal and Bakhtiari	y_6^D	Ilam
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{14}^W	Zanjan	y_{15}^D	Semnan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{21}^W	Kermanshah	y_{28}^D	Markazi
7	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_9^W	Chaharmahal and Bakhtiari	y_6^D	Ilam
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{14}^W	Zanjan	y_{15}^D	Semnan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{21}^W	Kermanshah	y_{28}^D	Markazi
8	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_{14}^W	Zanjan	y_6^D	Ilam
	y_{31}^C	Yazd	y_{19}^P	Qom	y_{21}^W	Kerman	y_{15}^D	Semnan
			y_{28}^P	Markazi	y_{22}^W	Kermanshah	y_{28}^D	Markazi
9	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_6^D	Ilam
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_9^W	Chaharmahal and Bakhtiari	y_9^D	Chaharmahal and Bakhtiari
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{14}^W	Zanjan	y_{15}^D	Semnan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{21}^W	Kermanshah	y_{28}^D	Markazi
10	y_4^C	Isfahan	y_9^P	Chaharmahal and Bakhtiari	y_7^W	Bushehr	y_2^D	Western Azarbaijan
	y_{12}^C	Northern Khorasan	y_{11}^P	Razavi Khorasan	y_8^W	Tehran	y_5^D	Alborz
	y_{14}^C	Zanjan	y_{13}^P	Khuzestan	y_9^W	Chaharmahal and Bakhtiari	y_6^D	Ilam
	y_{21}^C	Kerman	y_{19}^P	Qom	y_{14}^W	Zanjan	y_{24}^D	Golestan
	y_{31}^C	Yazd	y_{28}^P	Markazi	y_{21}^W	Kermanshah	y_{28}^D	Markazi

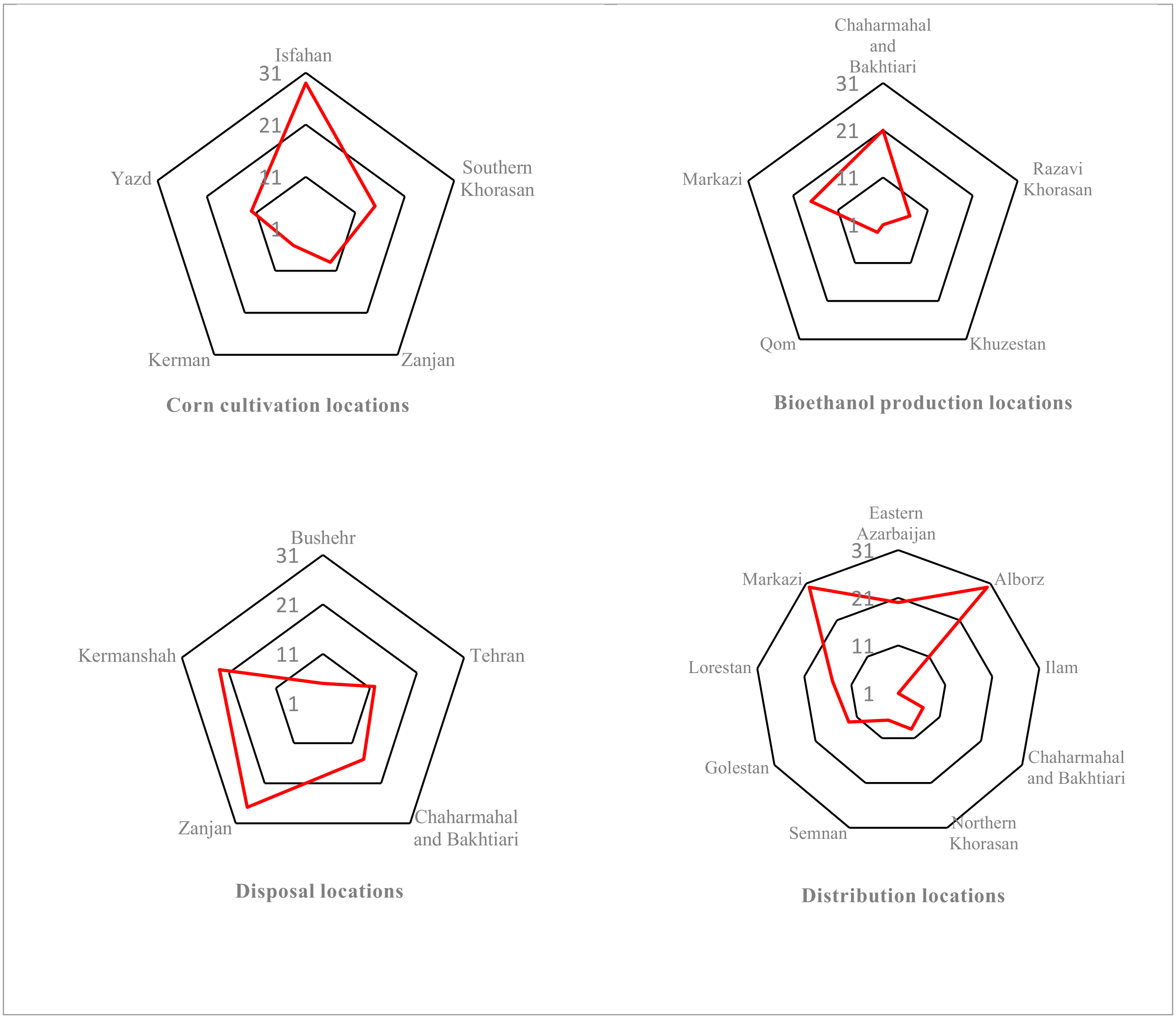

Fig. 5. Selected location and their MADM rank for the four tiers of the BSC.

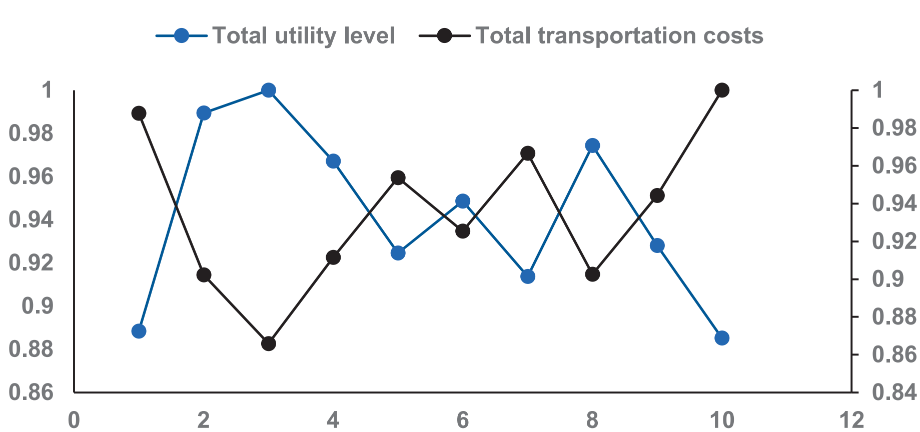

Fig. 6. A trade-off between total sustainability level and total transportation cost.

and biorefineries are the same among all of the non-dominated solutions (see Table 4), the centers selected for disposal and distribution sites have changed significantly in all the solutions provided by the algorithm (see Table 4). It is worth noting that Khuzestan and Ilam which are desirable places for biorefinery and waste disposal (see Table 2), are selected by the suggested model while the other two highly appropriate places (i.e. Kordestan and Hormozgan) are not among the solutions presented in Table 4.

Fig. 5 illustrates the rank of the selected locations, as determined by the bi-objective model, for the four tiers of the BSC network. It is evident

Table A

Parameters of the mathematical model for the example investigated in this paper.

Provinces	Index number	C_h^{TD}	C_k^{TP}	C_i^{TC}	Wc_m	Pc_k	V_h^T	N_d	V_i^C	α	V_{max}^W	V_{max}	V_{max}^C	W^C	W^P	W^W	W^D
Eastern Azarbaijan	1	24.5	24.5	24.5	70553278.32	1.04E + 08	95,000,000	17222691.14	191,066,400	0.875	7000	8679	7000	0.25	0.25	0.25	0.25
Western Azarbaijan	2	21.6	21.6	21.6	70553278.32	1.04E + 08	95,000,000	14383852.66	157,130,400								
Ardabil	3	24.1	24.1	24.1	70553278.32	1.04E + 08	95,000,000	5596419.138	75,041,400								
Isfahan	4	24.9	24.9	24.9	70553278.32	1.04E + 08	95,000,000	22558227.16	449,836,800								
Alborz	5	27.1	27.1	27.1	70553278.32	1.04E + 08	95,000,000	11948589.66	21,596,400								
Ilam	6	28.5	28.5	28.5	70553278.32	1.04E + 08	95,000,000	2555696.017	84,630,000								
Bushehr	7	24.5	24.5	24.5	70553278.32	1.04E + 08	95,000,000	5124977.586	97,305,600								
Tehran	8	28.6	28.6	28.6	70553278.32	1.04E + 08	95,000,000	58446228.51	58,968,000								
Chaharmahal and Bakhtiari	9	25.2	25.2	25.2	70553278.32	1.04E + 08	95,000,000	4175059.422	68,926,200								
Southern Khorasan	10	25.7	25.7	25.7	70553278.32	1.04E + 08	95,000,000	3387128.259	635,023,200								
Razavi Khorasan	11	23.4	23.4	23.4	70553278.32	1.04E + 08	95,000,000	28345086.3	449,895,600								
Northern Khorasan	12	25.9	25.9	25.9	70553278.32	1.04E + 08	95,000,000	3802069.069	118,297,200								
Khuzestan	13	23.2	23.2	23.2	70553278.32	1.04E + 08	95,000,000	20750604.3	290,845,800								
Zanjan	14	23.3	23.3	23.3	70553278.32	1.04E + 08	95,000,000	4658298.026	93,088,800								
Semnan	15	23.9	23.9	23.9	70553278.32	1.04E + 08	95,000,000	3094016.897	409,462,200								
Sistan and Baluchestan	16	24.5	24.5	24.5	70553278.32	1.04E + 08	95,000,000	12224415.12	787,508,400								
Fars	17	23.7	23.7	23.7	70553278.32	1.04E + 08	95,000,000	21370698.4	517,372,800								
Qazvin	18	24.6	24.6	24.6	70553278.32	1.04E + 08	95,000,000	5611136.819	65,675,400								
Qom	19	25.1	25.1	25.1	70553278.32	1.04E + 08	95,000,000	5692729.422	47,195,400								
Kordestan	20	22.5	22.5	22.5	70553278.32	1.04E + 08	95,000,000	7061539.836	121,031,400								
Kerman	21	27	27	27	70553278.32	1.04E + 08	95,000,000	13941128.43	785,736,000								
Kermanshah	22	24.7	24.7	24.7	70553278.32	1.04E + 08	95,000,000	8600808.397	105,037,800								
Kohgeluyeh and Boyer-Ahmad	23	24	24	24	70553278.32	1.04E + 08	95,000,000	3,141,117	65,364,600								
Golestan	24	25.6	25.6	25.6	70553278.32	1.04E + 08	95,000,000	8232469.905	85,600,200								
Gilan	25	24	24	24	70553278.32	1.04E + 08	95,000,000	11148152.21	61,786,200								
Lorestan	26	27.9	27.9	27.9	70553278.32	1.04E + 08	95,000,000	7755962.405	118,885,200								
Mazandaran	27	24.7	24.7	24.7	70553278.32	1.04E + 08	95,000,000	14464744.84	99,775,200								
Markazi	28	24	24	24	70553278.32	1.04E + 08	95,000,000	6297083.836	122,333,400								
Hormozgan	29	24	24	24	70553278.32	1.04E + 08	95,000,000	7825414.353	279,463,800								
Hamadan	30	24.4	24.4	24.4	70553278.32	1.04E + 08	95,000,000	7657220.466	81,870,600								
Yazd	31	25.3	25.3	25.3	70553278.32	1.04E + 08	95,000,000	5015434.164	321,930,000								

Table B
Distance between different provinces of Iran.

Provinces	East Azarbaijan	West Azarbaijan	Ardabil	Isfahan	Alborz	Ilam	Bushehr	Tehran	Chaharmahal and Bakhtiari	South Khorasan	Razavi Khorasan	North Khorasan	Khuzestan	Zanjan	Semnan	Sistan and Baluchestan
East Azarbaijan	0	308	219	1038	589	772	1560	599	1142	1912	1493	1321	1075	280	835	2166
West Azarbaijan	308	0	527	1074	721	766	1549	907	1178	2220	1802	1620	1064	588	1143	2264
Ardabil	219	527	0	1030	545	975	1610	591	1134	1814	1333	1080	1305	377	828	2154
Isfahan	1038	1074	1030	0	452	678	580	439	104	1173	1222	1152	745	757	675	1190
Alborz	589	721	545	452	0	691	1082	48	583	1174	954	790	842	293	271	1516
Ilam	772	766	975	678	691	0	932	710	719	1788	1604	1423	447	598	946	1868
Bushehr	1560	1549	1610	580	1082	932	0	1228	684	1599	1648	1941	485	1338	1464	1404
Tehran	599	907	591	439	48	710	1228	0	543	1313	894	713	874	319	236	1567
Chaharmahal and Bakhtiari	1142	1178	1134	104	583	719	684	543	0	1277	1326	1256	849	862	779	1294
South Khorasan	1912	2220	1814	1173	1174	1788	1599	1313	1277	0	481	734	1918	1623	1139	470
Razavi Khorasan	1493	1802	1333	1222	954	1604	1648	894	1326	481	0	253	1768	1213	658	951
North Khorasan	1321	1620	1080	1152	790	1423	1941	713	1256	734	253	0	1587	1032	543	1204
Khuzestan	1075	1064	1305	745	842	447	485	874	849	1918	1768	1587	0	967	1110	1759
Zanjan	280	588	377	757	293	598	1338	319	862	1623	1213	1032	967	0	555	1886
Semnan	835	1143	828	675	271	946	1464	236	779	1139	658	543	1110	555	0	1609
Sistan and Baluchestan	2166	2264	2154	1190	1516	1868	1404	1567	1294	470	951	1204	1759	1886	1609	0
Fars	1523	1559	1515	485	939	1100	304	924	589	1325	1374	1637	659	1243	1160	1100
Qazvin	455	763	451	480	110	617	1060	150	584	1463	1044	863	882	175	386	1717
Qom	731	1039	723	279	189	684	876	132	367	1445	1026	845	715	451	368	1375
Kordestan	52	446	655	627	505	320	1108	501	732	1814	1395	1214	623	278	737	1818
Kerman	1637	1735	1629	661	1026	1339	875	1038	765	999	889	1142	1230	1357	1274	529
Kermanshah	588	582	791	653	519	184	972	526	731	1800	1420	1239	487	414	762	1817
Kohgeluyeh and Boyer-Ahmad	1337	1373	1329	299	797	977	281	738	229	1405	1454	1451	433	1057	974	1274
Golestan	996	1304	764	836	454	1107	1625	397	940	1050	569	316	1271	716	377	1520
Gilan	485	793	266	764	284	774	1524	325	868	1548	1067	814	1039	348	561	1892
Lorestan	879	783	930	370	505	308	860	499	474	1543	1393	1212	375	592	735	1560
Mazandaran	866	1174	634	706	320	977	1495	267	810	1180	699	446	1141	586	205	1650
Markazi	785	786	843	288	298	514	868	293	392	1606	1187	1006	581	505	529	1478
Hormozgan	1933	2026	1925	975	1317	1729	927	1334	1061	1213	1374	1627	1278	1653	1570	743
Hamadan	609	610	667	464	337	373	1044	337	568	1637	1231	1050	638	329	573	1654
Yazd	1276	1374	1268	300	664	978	726	677	404	873	922	1390	1081	996	913	890

Provinces	Fars	Qazvin	Qom	Kordestan	Kerman	Kermanshah	Kohgeluyeh and Boyer-Ahmad	Golestan	Gilan	Lorestan	Mazandaran	Markazi	Hormozgan	Hamadan	Yazd
East Azarbaijan	1523	455	731	52	1637	588	1337	996	485	879	866	785	1933	609	1276
West Azarbaijan	1559	763	1039	446	1735	582	1373	1304	793	783	1174	786	2026	610	1374
Ardabil	1515	451	723	655	1629	791	1329	764	266	930	634	843	1925	667	1268
Isfahan	485	480	279	627	661	653	299	836	764	370	706	288	975	464	300
Alborz	939	110	189	505	1026	519	797	454	284	505	320	298	1317	337	664
Ilam	1100	617	684	320	1339	184	977	1107	774	308	977	514	1729	373	978
Bushehr	304	1060	876	1108	875	972	281	1625	1524	860	1495	868	927	1044	726
Tehran	924	150	132	501	1038	526	738	397	325	499	267	293	1334	337	677
Chaharmahal and Bakhtiari	589	584	367	732	765	731	229	940	868	474	810	392	1061	568	404
South Khorasan	1325	1463	1445	1814	999	1800	1405	1050	1548	1543	1180	1606	1213	1637	873
Razavi Khorasan	1374	1044	1026	1395	889	1420	1454	569	1067	1393	699	1187	1374	1231	922
North Khorasan	1637	863	845	1214	1142	1239	1451	316	814	1212	446	1006	1627	1050	1390
Khuzestan	659	882	715	623	1230	487	433	1271	1039	375	1141	581	1278	638	1081
Zanjan	1243	175	451	278	1357	414	1057	716	348	592	586	505	1653	329	996
Semnan	1160	386	368	737	1274	762	974	377	561	735	205	529	1570	573	913
Sistan and Baluchestan	1100	1717	1375	1818	529	1817	1274	1520	1892	1560	1650	1478	743	1654	890
Fars	0	965	764	1113	571	1112	174	1321	1249	855	1191	773	619	949	425

(*continued on next page*)

Table B (*continued*)

Provinces	Fars	Qazvin	Qom	Kordestan	Kerman	Kermanshah	Kohgeluyeh and Boyer-Ahmad	Golestan	Gilan	Lorestan	Mazandaran	Markazi	Hormozgan	Hamadan	Yazd
Qazvin	965	0	282	453	1172	433	779	547	185	507	417	303	1455	244	780
Qom	764	282	0	474	846	499	595	529	457	340	399	134	1142	289	485
Kordestan	1113	453	474	0	1289	136	927	898	565	427	768	340	1585	164	928
Kerman	571	1172	846	1289	0	1288	745	1435	1363	1031	1305	949	485	1125	361
Kermanshah	1112	433	499	136	1288	0	952	923	590	320	793	365	1769	189	953
Kohgeluyeh and Boyer-Ahmad	174	779	595	927	745	952	0	1135	739	699	1005	587	756	763	532
Golestan	1321	547	529	898	1435	923	1135	0	498	896	130	690	1731	734	1074
Gilan	1249	185	457	565	1363	590	739	498	0	664	368	577	1659	401	1002
Lorestan	855	507	340	427	1031	320	699	896	664	0	766	206	1327	263	670
Mazandaran	1191	417	399	768	1305	793	1005	130	368	766	0	560	1601	604	944
Markazi	773	303	134	340	949	365	587	690	577	206	560	0	1245	176	588
Hormozgan	619	1455	1142	1585	485	1769	756	1731	1659	1327	1601	1245	0	1421	657
Hamadan	949	244	289	164	1125	189	763	734	401	263	604	176	1421	0	734
Yazd	425	780	485	928	361	953	532	1074	1002	670	944	588	657	734	0

that the selected alternatives for the bioethanol production locations have superior performance in the additive value function (Equation 15) compared to the other three facilities, likely due to the close geographical proximity of Markazi, Qom, and Khuzestan. This is likely caused by the significant influence of total transportation costs on the geographical distribution of Iranian provinces. For instance, as Fig. 5 indicates, some of the selected distribution locations have zero transportation cost (e.g., Markazi, where the location of production centre and the distribution centre are the same) yet have the lowest additive value function (Equation 15).

As Fig. 6 indicates, there is a trade-off between the total sustainability index and total transportation costs, as the higher values of the first objective function correspond to the lower values of the second objective function, and vice versa. For instance, consider Sol. 3 which is the best solution in terms of total sustainability index, while ranks last among the other solutions as long as the second objective function is concerned. Indeed, by choosing Sol. 3 as the ultimate solution, we sacrifice the total transportation cost in favor of a higher sustainability level (see Fig. 6). We present the other results of this example in Tables C to N in the Appendix.

It is worth noting that, among ten solutions, just Sol.6 provides an appropriate balance between the two objective functions (see Fig. 6).

7. Conclusion and future works

In the bioethanol supply chain, it is important to consider different sustainability factors in the location evaluation/selection process. For that purpose, we used a two-step structure in this paper. First using a multi- attribute decision-making model, the best-worst method, we calculated the sustainability index of the alternatives in different levels of the bioethanol supply chain (i.e. provinces of Iran) considering the attributes categorized into economy, social and environmental dimensions of sustainability. Then, using the sustainability score of candidate places as the parameters of the first objective function)namely sustainability value function (, and also, the transportation costs in the BSC network as the second objective function, we developed a bi-objective multi-level bioethanol supply chain model in this paper. Approximating the sustainability value function which significantly reduces the number of variables and constraints, is an important part of the proposed model to which the relevant literature has not paid enough attention, yet. We suggested a new Nested bi-objective Optimization Genetic Algorithm to solve the proposed model. The suggested algorithm used the property of the search space of the problem and independency among the variables and converted the problem to three less complex single-objective optimization subproblems. It applied the solutions of these subproblems in a unified solution for the main problem by using a general multi-objective optimization algorithm. We evaluated the efficiency of the proposed structure using a set of data collected from Iran. Determining the optimal location of cultivation lands, distribution centers, biorefineries, and waste disposal sites along with the flow of raw material and bioethanol in the BSC network are the outputs of multi-attribute- bi-objective structure proposed model.

Identifying and categorizing the factors contributing to the location selection of facilities in the bioethanol supply chain, provide useful insights for both public policymakers and scholars. To better use of existing potentials, considering the proposed framework of attributes, the public policymakers can prioritize the measures to facilitate the affairs in the three dimensions of sustainability. Scholars can also concentrate on the measures of sustainability to prioritize the requirements of bioethanol production technologies.

The suggested structure can be applied to model the supply chain of various products (such as biodiesel and biomethane) where the sustainability concerns along with transportation costs need to be considered in the entire supply chain of the products. To satisfy the demand at the right time, future research can concentrate on the coverage radius of distribution centers, and also other types of transportation modes.

Table C
The amount of biomass transferred from farmlands to biorefineries.

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
x_{4-9}	90104997.46	89171438.51	73970119.30	102449547.48	97983844.80	94992307.49	86473307.97	104,000,000	93130098.13	86534422.54
x_{12-11}	94194195.86	104,000,000	104,000,000	104,000,000	82769907.95	104,000,000	95684164.33	104,000,000	98068912.92	93699783.88
x_{14-19}	84311775.5	93,088,800	93,088,800	93,088,800	93,088,800	79648063.78	85318294.33	93,088,800	87560110.08	83550248.97
x_{21-9}	4089198.4	14828561.49	30029880.69	1550452.51	6016155.19	9007692.50	9210856.35	0	4938814.78	7165361.33
x_{21-13}	94194195.86	104,000,000	104,000,000	104,000,000	104,000,000	104,000,000	95684164.33	104,000,000	98068912.92	93699783.88
x_{31-28}	94194195.86	104,000,000	104,000,000	104,000,000	104,000,000	104,000,000	95684164.33	104,000,000	98068912.92	93699783.88

CRediT authorship contribution statement

Siamak Kheybari: Conceptualization, Investigation, Methodology, Resources, Validation, Data curation, Formal analysis, Funding acquisition, Software, Visualization, Writing - original draft, Writing - review & editing. **Mansoor Davoodi Monfared:** Investigation, Methodology, Validation, Data curation, Software, Writing - original draft, Writing - review & editing. **Amirhossein Salamirad:** Investigation, Validation, Data curation, Resources, Writing - original draft. **Jafar Rezaei:** Investigation, Validation, Formal analysis, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

BWM.

The BWM includes five steps that are described below:

1. Identify decision making criteria $\{c_1, c_2, \cdots, c_n\}$ by the decision-makers/experts.
2. Identify the Best (B) and Worst (W) criteria by the decision-makers/experts.
3. Determin the preference of B over other criteria by the decision-makers/experts using the 1 to 9 scale. 1 indicates equally important and 9 is extremely more important. The output of this step is $A_B = \left(a_{B1}, a_{B2}, \cdots, a_{Bj}, \cdots., a_{Bn}\right)$ where a_{Bj} shows the comparison of B over criterion j.
4. Determine the preference of other criteria over W *by the decision-makers/experts* using the 1 to 9 scale. We show the outcome of this step using vector $A_w = \left(a_{1W}, a_{2W}, \cdots, a_{jW}, \cdots., a_{nW}\right)$, where a_{jW} shows the comparison of criterion j over W.
5. Calculate the optimal weights $\left(w^*_1, w^*_2, \cdots, w^*_n\right)$ using the following model:

$$\min \max_j \{ |w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W| \}$$

Such that

$$\sum_{j=1}^{n} w_j = 1$$

$$w_j \geq 0, \text{ for all } j \tag{1}$$

where the objective function minimizes the maximum absolute differences $\{ |w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W| \}$ for all j.

Model 1 can be transferred into:

$\min \xi$

Such that

$$|w_B - a_{Bj}w_j| \leq \xi, \quad \text{for all } j$$

$$|w_j - a_{jW}w_W| \leq \xi, \quad \text{for all } j$$

Table D
The amount of wastes transferred from biorefineries to disposal sites.

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
R_{9-7}	70471.33	5525351.73	592121.96	2307427.69	1639905.43	12095210.93	373085.05	15499.08	9983814.16	4154752.28
R_{9-8}	0	4086630.18	1012021.85	0	1838.16	55242.62	76793.95	63384.20	1773687.84	574579.41
R_{9-9}	0.45	0	0	259631.87	0	63201.88	11394552.20	0	46.99	4590288.13
R_{9-14}	172137.33	10735.25	7429755.40	719.10	2846758.36	714912.78	115951.09	260.07	495167.60	1650250.26
R_{9-21}	10970640.41	3359851.91	3279179.60	11.13	8511498.03	71431.77	138.23	11280446.55	5897.50	742602.88
R_{9-22}	561025.25	17430.91	686921.18	10432210.19	0	0	0	1640410.07	0	0
R_{11-7}	41055.80	3009160.73	228256.25	1528.11	3841.45	786890.12	2006603.47	121298.97	4852987.56	313153.50
R_{11-8}	0	1.57	388047.41	0	1980834.43	11007403.36	9298.27	8679.34	5860608.54	10125616.66
R_{11-9}	9367501.99	0	0	165180.69	2867.97	210127.17	1433837.19	0	1518903.01	918582.60
R_{11-14}	2365702.19	1366845.13	4920417.40	2743329.83	65129.38	991024.99	30.76	6134270.45	4588.35	546.73
R_{11-21}	0	101557.65	4613779.19	9955331.09	8293565.24	4554.34	8510750.83	3787600.28	21526.62	354573.47
R_{11-22}	14.50	8522434.90	2849499.72	134630.26	0	0	0	2948150.93	0	0
R_{13-7}	14448.76	357141.88	197.78	397100.42	3243568.27	1099042.20	20.21	24791.08	3434.20	24644.43
R_{13-8}	0	72480.84	60760.07	0	759001.27	17696.19	0	132.65	107547.11	3652374.79
R_{13-9}	5545585.52	0	0	4240199.21	848839.74	11501728.31	10161303.48	0	11826821.44	2580627.86
R_{13-14}	5681301.37	2754976.47	91552.97	2769.32	1036472.44	377726.11	202.41	5392636.96	308463.06	5226263.76
R_{13-21}	323751.38	9251843.87	6578374.68	8359931.03	112118.26	3807.16	1798994.42	7048550.25	12348.27	228562.13
R_{13-22}	209187.43	563556.92	6269114.48	0	0	0	0	533889.04	0	0
R_{19-7}	2105230.11	1058080.46	228397.35	11573.70	2746674.02	62681.83	4089689.71	10547949.05	802.21	0.52
R_{19-8}	0	531.05	28477.03	0	877296.42	3620338.71	51.78	600832.73	271188.58	1761441.64
R_{19-9}	17623.77	0	0	5677302.12	7986593.75	13.48	2213784.17	0	10665863.09	6021625.32
R_{19-14}	33.35	50062.39	3184486.14	867630.33	0.35	2869190.73	1444.32	86719.70	6914.35	2611791.62
R_{19-21}	32686.07	576274.68	0	11333.71	25535.43	3403783.20	4359816.79	400582.77	245.52	48922.00
R_{19-22}	8383398.62	9951151.39	8194739.46	5068260.11	0	0	0	15.72	0	0
R_{28-7}	4700631.91	1782607.23	22.76	2446669.65	2145390.05	89919.59	4292942.21	74338.50	970770.88	2906161.93
R_{28-8}	0	11006314.68	15970.55	0	24563.75	1491262.26	7636707.68	143852.65	4346577.97	199801.77
R_{28-9}	5373716.51	0	0	298220.52	9339.27	760148.99	28022.25	0	2408273.15	0
R_{28-14}	398022.96	137980.95	12737307.86	3208198.91	1055695.04	8520624.18	103.98	6106.80	2364454.98	8606469.53
R_{28-21}	1300980.88	9.34	1629.40	691.21	9765011.87	2138044.96	2744.39	0	2168537.11	39.74
R_{28-22}	922.21	73087.78	245069.41	7046219.68	0	0	0	12775702.03	0	0

Table E
The amount of bioethanol transferred from biorefineries to distribution centers.

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
l_{9-2}	52576954.28	0	9882873.01	671625.96	15686.80	241991.07	215539.86	38262279.94	23798948.11	725301.44
l_{9-5}	9495532.66	22543.31	0	88973673.87	860728.23	49918303.61	9068428.17	480.76	0	9239493.71
l_{9-6}	148606.84	73423033.93	22501820.29	4901.09	3143.07	35766209.40	6551652.64	101979.79	651.69	7312223.80
l_{9-9}	0	0	56711237.72	0	88337309.10	0	0	0	46449401.52	0
l_{9-10}	0	8484938.79	774623.62	0	0	0	0	0	0	0
l_{9-15}	0	1143979.74	1129445.34	11960.65	0	230692.62	5371924.06	32468413.57	5736661.12	0
l_{9-24}	0	0	0	0	0	0	0	0	0	4266090.29
l_{9-26}	20197959.49	0	0	0	0	0	0	0	0	0
l_{9-28}	868.10	7925504.20	1129445.34	1337838.41	1783132.77	4842803.28	62516099.04	20166845.91	9824636.35	60444201.63
l_{11-2}	40.85	0	4120128.76	57731.69	290041.03	261569.80	5656.97	1880621.65	22780740.61	5745621.53
l_{11-5}	163359.23	11078763.08	0	57731.69	71831894.87	927.11	1.36	56903848.85	0	0.49
l_{11-6}	77123.57	170256.94	50957721.97	0	44.23	5253270.21	59457354.70	19111164.79	50794.50	668.44
l_{11-9}	0	0	12437318.94	0	23747.20	0	0	0	42177336.77	0
l_{11-10}		427845.59	769063.98	0	0	0	0	0	0	0
l_{11-15}		79319066.87	0	90403021.19	0	85484232.86	1375933.02	4194.17	3265365.19	0
l_{11-24}	0	0	0	0	0	0	0	0	0	67280317.11
l_{11-26}	460.92	0	0	0	0	0	0	0	0	0
l_{11-28}	82178936.79	4067.50	22715766.32	171603.09	277942.09	0	22884697.71	13100170.52	17536061.71	8960703.31
l_{13-2}	18502317.26		6.25	88924711.77	4555.02	86338337.31	51089258.62	5245793.14	27350747.92	69371680.82
l_{13-5}	43134.95	1614304.80	0	4201.59	5530.94	0	24140149.94	8730538.25	0	54685.67
l_{13-6}	63768109.20	19424284.52	148400.30	2050336.49	62074836.97	945762.25	3803126.64	72076380.23	0	6785082.89
l_{13-9}	0	0	17727411.16	0	20.40	0	0	0	31126.45	
l_{13-10}	0	69261546.44	10412215.89	0	0	0	0	0	0	
l_{13-15}	0	695900.25	0	18860.25	0	2832074.58	1646931.12	2269141.28	0	
l_{13-24}	0	0	0	0	0	0	0	0	0	6002.89
l_{13-26}	1546.6	0	0	0	0	0	0	0	0	0
l_{13-28}	104813.35	3963.96	62711966.36	1889.88	28915056.66	883825.84	3044177.44	2678147.08	58428424.42	5769858.61
l_{19-2}	5097690.11		2735470.09	275580.37	11824.26	82.07	158.28	46952669.20	4550118.97	569650.34
l_{19-5}	769629.24	81426161.45	0	380.61	15502987.09	1.16	56647704.14	5939528.16	0	58500.71
l_{19-6}	31.71	8.82	4677912.76	258348.92	31344936.63	52721602.78	16662856.52	203789.85	893.96	56231367.90
l_{19-9}	0	0	13338.63	0	2326910.79	0	0	0	59.83	0
l_{19-10}	0	24897.68	73990114.52	0	0	0	0	0	0	0
l_{19-15}	0	1632.04	0	9236.62	0	3524357.94	627238.97	28356014.37	71392151.19	0
l_{19-24}										13486896.99
l_{19-26}	67900906.73	0	0	0	0	0	0	0	0	0
l_{19-28}	4545.81	0	35863.98	80909153.46	32266041.20	13446011.83	715549.61	698.39	671872.35	2760051.89
l_{28-2}	534939.80	0	76915417.43	1747121.92	87320844.46	599761.61	5441.39	43.60	11671025.04	1228056.14
l_{28-5}	63385618.94	24.14	0	301120.41	10948.03	35290524.45	536711.74	12921538.02	0	80736746.04
l_{28-6}	14903654.08	144289.22	12925521.95	78477784.89	265086.27	116.70	1298447.85	677775.19	74109764.41	14.62
l_{28-9}	0	0	1154581.88	0	3395468.15	0	0	0	505.33	0
l_{28-10}	0	11178150.64	4284.96	0	0	0	0	0	0	0
l_{28-15}	0	19646.39	0	8.04	0	0	81764302.08	20498344.61	28914.92	0
l_{28-15}	0	0	0	0	0	0	0	0	0	0.25
l_{28-26}	3593436.65	0	0	0	0	0	0	0	0	0
l_{28-28}	2271.89	79657889.58	193.75	10473964.71	7653.06	55109597.23	118740.71	56902298.55	89.08	22493.83

Table F
The amount of bioethanol delivered to demand nodes from Western Azarbaijan (index number = 2).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{2-1}	11949666.95	0	106.5134	0	6,184,652	56783.96	207450.9	7,773,207	44304.28	132780.9
D_{2-2}	827375.2752	0	31906.18	13,681,251	13,499,250	823,165	0	14,120,966	246755.5	12,576,083
D_{2-3}	286690.6717	0	0	227410.3	331822.1	16940.27	381261.2	2,621,060	5116.656	3,526,080
D_{2-4}	22923.22853	0	2,536,280	296391.6	143706.3	249214.3	6,810,958	4,472,492	8,982,442	3,162,114
D_{2-5}	72786.19992	0	134614.6	102279.1	222.0439	849089.2	111706.5	16471.84	7,014,656	85772.03
D_{2-6}	2081992.024	0	13975.88	0	1,456,118	692.8196	0	472414.8	302659.7	1,163,022
D_{2-7}	0	0	126767.3	1,899,023	1,537,456	2,319,086	9863.593	309275.7	658.7934	0
D_{2-8}	15166063.17	0	12,023,897	1,398,279	32,962,606	34,789,464	0	390732.3	42,236,968	9,801,358
D_{2-9}	38554.64125	0	939.1276	15081.35	2,160,641	29583.48	583012.7	59989.59	11248.12	26884.04
D_{2-10}	1662.60482	0	7580.465	2,230,205	1,344,975	2,767,899	355694.3	599729.9	294619.8	2,343,939
D_{2-11}	2257373.289	0	45851.61	928090.1	605588.5	1,501,499	7,744,877	4,774,635	6,097,319	13,782,980
D_{2-12}	79075.68956	0	180448.3	133400.6	1927.247	34123.99	417.3791	3,773,221	10108.46	17829.09
D_{2-13}	4620675.187	0	2,366,395	148143.2	1,856,643	4,135,638	1,326,310	9841.089	93845.8	4,300,264
D_{2-14}	0	0	20921.9	3,844,898	822,457	0	37444.84	212995.6	99927.76	0
D_{2-15}	2037.440409	0	946.8922	100534.1	447673.2	189242.6	1,331,655	1442.217	352005.5	0
D_{2-16}	312548.871	0	0	327534.5	2,507,571	20056.77	2921.209	3,131,222	199872.4	1,902,609
D_{2-17}	18817496.28	0	19,896,934	214304.2	1,531,426	0	5,683,353	2,566,085	9,771,352	5,505,454
D_{2-18}	29399.12157	0	0	0	2,027,304	27521.38	193448.5	0	1,323,140	38905.4
D_{2-19}	66900.01489	0	1,210,375	5117.431	4,459,917	0	2,107,769	4,987,029	3,122,400	0
D_{2-20}	0	0	179175.6	401348.5	2,710,428	4,370,489	0	129234.1	1,687,483	6,529,547
D_{2-21}	18191.68556	0	0	359,397	174712.5	0	3,706,511	31506.38	53780.28	2376.324
D_{2-22}	2158023.589	0	118,438	468.8483	0	3,717,319	481968.4	2809.298	3,431,323	556674.1
D_{2-23}	91423.22957	0	10447.67	639667.9	447,742	1,020,102	1,414,007	49920.63	174689.8	566976.9
D_{2-24}	936.2311728	0	5,382,060	323820.4	153483.1	539613.9	6,534,900	2,429,071	258108.8	2,790,043
D_{2-25}	211969.6605	0	0	695877.5	1006.436	1,508,759	1433.434	10,966,350	17769.27	2,247,625
D_{2-26}	0	0	3,899,641	4,278,031	21090.9	118343.1	150615.7	4,828,484	12978.8	215945.2
D_{2-27}	0	0	9,954,342	4626.621	401114.5	11,243,382	2458.378	2,432,697	60829.87	1,223,439
D_{2-28}	5200735.347	0	0	1461.062	0	0	4,334,871	91.4593	1380.499	2110.962
D_{2-29}	1003100.905	0	0	1,655,609	2,864,574	392743.1	2,167,403	2905.642	3,502,691	0
D_{2-30}	731416.7492	0	0	5,483,405	541912.1	35.76458	3,822,705	535411.3	302859.2	0
D_{2-31}	261717.5858	0	3,560,624	114970.9	1,258,508	90792.74	709.9519	7,773,207	5528.621	506.7572

Table G
The amount of bioethanol delivered to demand nodes from Alborz (index number = 5).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{5-1}	3,863,798	11,228,543	0	15865082.12	981778.1	0	3,259,057	380.9337743	0	4,810,590
D_{5-2}	2,609,039	3,609,076	0	11527.60498	860453.3	1,098,623	410292.6	19441.82309	0	219,689
D_{5-3}	376259.4	5,351,814	0	5368424.682	300615.7	456661.9	3,333,714	523107.3004	0	1,227,040
D_{5-4}	1,729,222	239,616	0	4192999.8	1,286,334	50047.88	288598.9	11492415.1	0	56324.98
D_{5-5}	1,750,748	2,878,719	0	1633975.901	148149.7	1,182,484	1,215,959	16367.80185	0	3514.871
D_{5-6}	2128.322	1,421,953	0	194254.1386	1,070,045	2,016,150	123,681	894700.2435	0	3390.576
D_{5-7}	4,087,782	2,157,211	0	267455.9151	2,215,406	396427.9	13424.63	323898.9013	0	1,906,389
D_{5-8}	3,792,630	14,859,900	0	138123.1867	23,364,158	11,761,410	38,360,523	11981.87628	0	0
D_{5-9}	1,229,946	640822.8	0	0	180807.4	3,504,561	1,226,291	349522.9726	0	2,606,435
D_{5-10}	109214.6	730335.2	0	0	659141.3	403647.3	32599.26	248522.2695	0	27345.06
D_{5-11}	1,685,907	152051.7	0	2337554.372	9,535,745	0	0	1007.640497	0	722510.5
D_{5-12}	1,169,510	0	0	49732.17839	4239.109	107,092	1,521,083	139.2406963	0	840268.5
D_{5-13}	1,099,274	819623.2	0	782025.9377	3,134,510	835323.6	19,145,770	19972.76451	0	0
D_{5-14}	1,717,797	32296.76	0	580559.2674	938487.8	749.8392	1,224,508	348221.978	0	211,785
D_{5-15}	414988.7	753.3266	0	421929.1813	1,209,881	848,134	3028.175	11652.44745	0	2,773,205
D_{5-16}	5,939,222	153,000	0	1305547.093	568010.7	5,298,992	1,622,432	1068165.594	0	5648.089
D_{5-17}	1,245,091	18,721,416	0	19367775.32	247825.1	13,777,122	27502.33	7128180.507	0	15,633,328
D_{5-18}	970499.8	103618.8	0	4659585.79	552418.3	2,977,288	496,272	5073176.839	0	0
D_{5-19}	3,342,670	2,690,098	0	62491.96053	160159.3	4,693,674	47665.85	379973.321	0	5,683,168
D_{5-20}	369308.9	49591.71	0	46373.63667	4,344,812	1,697,466	432724.2	104777.3059	0	2397.572
D_{5-21}	0	1,201,133	0	13575913.7	114037.9	6,028,016	5617.952	8208308.446	0	13,083,659
D_{5-22}	3,714,877	78185.83	0	7664794.634	5,264,693	1,546,215	221965.9	1794097.881	0	1,293,552
D_{5-23}	628776.4	1,004,484	0	2364314.11	83195.4	735086.6	1,124,522	244364.3241	0	0
D_{5-24}	7,844,013	110700.7	0	136103.8967	80997.9	2,261,095	185241.9	1120290.708	0	825,033
D_{5-25}	181474.8	9,610,543	0	61922.92131	6,577,374	545715.4	12165.42	7506.417135	0	4,618,332
D_{5-26}	4051.527	3,636,493	0	0	4,884,170	3,003,955	4556.875	3063.592091	0	6,290,215
D_{5-27}	29573.22	61327.42	0	24587.88377	1539.396	2,653,010	86695.08	3,980,337	0	527254.7
D_{5-28}	756554.9	4,675,563	0	39994.91655	2,491,331	888006.7	402942.3	46642.43899	0	77143.34
D_{5-29}	3,779,890	2,479,210	0	3908824.309	91.82761	39534.74	496199.1	1197185.043	0	662705.1
D_{5-30}	2404.012	27514.96	0	11809.62198	5,922,687	728408.6	2,675,588	34185.13756	0	7,335,906
D_{5-31}	2,685,886	2,106,018	0	0	2,383,341	1,532,632	2,627,997	112226.4404	0	3495.048

Table H
The amount of bioethanol delivered to demand nodes from Ilam (index number = 6).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{6-1}	1878.911	1,105,465	6,252,801	936.1638	5,423,789	7,395,132	11,251,343	0	5,903,097	1998.896
D_{6-2}	15006.8	58508.04	9,144,969	111940.9	14830.74	3,469,418	13,548,754	50437.85	2,770,471	39960.57
D_{6-3}	126,404	208108.9	1,285,120	0	86103.28	4,913,443	511003.5	1,211,843	532.9213	71370.68
D_{6-4}	20,770,350	68596.19	13980.94	400750.6	7874.144	75550.84	12,882,248	6,436,538	1,123,316	3914.331
D_{6-5}	276756.5	3,733,174	9,801,610	5883.349	109263.1	10398.45	13309.98	5,561,954	302269.9	132261.9
D_{6-6}	62424.95	2224.432	99964.79	180748.5	17464.56	1844.539	5334.578	0	37454.74	0
D_{6-7}	444108.8	4311.713	1425.075	504.5972	356409.9	497901.9	4,505,595	2151.002	597651.4	252473.3
D_{6-8}	149651.8	36,014,464	9,876,378	25,251,380	1,912,738	7,215,348	18,544,880	4,230,852	415446.3	42,097,412
D_{6-9}	2,723,873	0	256960.4	2,027,763	147120.7	638778.4	2,113,969	614579.2	5661.731	12553.35
D_{6-10}	4849.733	0	442559.4	0	82993.32	147356.4	97234.26	299878.7	1,433,484	565132.1
D_{6-11}	1,045,454	8,571,662	8,856,383	14,997,611	3,110,242	0	2,931,670	21,125,315	2077.342	0
D_{6-12}	740.3496	2332.302	3,418,532	88971.88	0	3,659,709	935.3875	17570.47	17455.54	54336.56
D_{6-13}	13,812,672	17,575,960	357323.5	161515.3	5767.998	8,801,666	414.8401	231423.6	20,031,084	3,539,440
D_{6-14}	488359.6	9553.81	4,041,521	0	1,389,672	3,712,379	121.5692	3,328,772	0	874550.3
D_{6-15}	128682.4	140709.9	3,051,107	2,107,643	0	1,918,452	0	61602.75	26615.12	1316.96
D_{6-16}	64589.16	672,916	404579.1	4,563,591	9,125,537	1,580,553	2,217,775	1,609,733	28048.2	4753.587
D_{6-17}	1,039,999	2,460,261	7314.919	1,413,213	18,613,278	6,698,568	623.5748	29145.03	6646.698	1067.911
D_{6-18}	233530.3	1,043,567	722661.5	0	51724.27	269244.4	2,589,153	78555.92	7213.801	399597.7
D_{6-19}	1,534,086	205643.3	660066.6	558060.9	9018.711	997193.4	352462.2	240309.5	1,849,931	451.0632
D_{6-20}	2,985,481	0	3,810,499	4,243,697	0	0	1,024,973	6,361,634	550.5352	100782.6
D_{6-21}	46265.18	5,854,849	1,123,887	0	55099.97	7,869,344	0	5,378,519	17662.2	855,093
D_{6-22}	518414.8	5535.38	46488.49	931264.2	1,064,349	7210.776	1,545,047	5,560,868	201460.9	913.0729
D_{6-23}	30225.97	539970.9	7301.538	135773.7	2,537,737	0	64638.96	2,807,464	2,846,171	1,919,508
D_{6-24}	180,331	4,760,268	225,143	1984.263	70744.55	2,082,415	0	1,495,559	289.017	148691.7
D_{6-25}	4,970,250	200.7299	41550.3	1,334,422	90413.22	1,898,317	1,285,376	9352.094	9,256,348	4,027,833
D_{6-26}	5,433,806	1,311,174	0	176378.1	985785.4	1,791,212	3,329,007	2,788,000	5626.789	1122.738
D_{6-27}	0	111.3928	3,529,313	14,351,049	13,430,529	6033.635	711.7183	8,047,418	46039.59	1,061,736
D_{6-28}	77965.07	368515.6	2,963,103	1,071,173	0	0	47004.8	66509.19	0	1,476,845
D_{6-29}	2,720,319	137307.8	393.4618	1,394,613	18320.64	2,603,937	261322.5	6,460,765	310230.6	5,189,936
D_{6-30}	6,629,858	155299.2	4,068,111	4466.163	261681.3	2,399,806	198059.9	10917.62	2,271,278	102723.7
D_{6-31}	1,229,405	649499.5	129048.1	4,897,775	283330.8	18672.73	871783.5	168356.1	4,323,129	4,999,991

Table I
The amount of bioethanol delivered to demand nodes from Kohgeluyeh and Boyer-Ahmad (index number = 9).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{9-1}	0	0	0		2,484,617	0	0	0	3,224,439	0
D_{9-2}	0	0	3,572,776		0	0	0	0	2,393,851	0
D_{9-3}	0	0	76894.41		4,813,803	0	0	0	251573.1	0
D_{9-4}	0	0	247551.1		18,395,094	0	0	0	11,027,795	0
D_{9-5}	0	0	97745.99		11,690,955	0	0	0	1,656,471	0
D_{9-6}	0	0	34139.1		6969.201	0	0	0	2,103,168	0
D_{9-7}	0	0	1509.151		0	0	0	0	0	0
D_{9-8}	0	0	102895.7		10544.77	0	0	0	8,456,219	0
D_{9-9}	0	0	1,410,843		1,683,686	0	0	0	176,970	0
D_{9-10}	0	0	0		1,267,376	0	0	0	823.5699	0
D_{9-11}	0	0	19,432,665		2,508,116	0	0	0	22,098,215	0
D_{9-12}	0	0	0		3,795,903	0	0	0	45670.22	0
D_{9-13}	0	0	17,543,791		6,580,282	0	0	0	0	0
D_{9-14}	0	0	267040.2		1,484,098	0	0	0	2,060,929	0
D_{9-15}	0	0	22078.11		135648.1	0	0	0	611044.3	0
D_{9-16}	0	0	0		2706.922	0	0	0	1,053,494	0
D_{9-17}	0	0	1,329,735		90893.39	0	0	0	506446.3	0
D_{9-18}	0	0	570446.8		2,079,169	0	0	0	864.1163	0
D_{9-19}	0	0	168,429		0	0	0	0	720398.6	0
D_{9-20}	0	0	3,066,205		5733.915	0	0	0	72815.45	0
D_{9-21}	0	0	0		534153.9	0	0	0	643333.3	0
D_{9-22}	0	0	7,824,130		1,756,672	0	0	0	20235.28	0
D_{9-23}	0	0	784780.9		72442.4	0	0	0	117450.2	0
D_{9-24}	0	0	111715.5		7,361,780	0	0	0	1,278,813	0
D_{9-25}	0	0	1,865,331		3,082,899	0	0	0	1,831,289	0
D_{9-26}	0	0	198641.6		0	0	0	0	3,584,598	0
D_{9-27}	0	0	980734.3		50012.69	0	0	0	51389.8	0
D_{9-28}	0	0	1,106,077		3,805,752	0	0	0	4,727,731	0
D_{9-29}	0	0	260068.8		46511.61	0	0	0	28657.32	0
D_{9-30}	0	0	3,562,668		849441.7	0	0	0	13751.25	0
D_{9-31}	0	0	24293.82		0	0	0	0	536088.8	0

Table J
The amount of bioethanol delivered to demand nodes from Southern Khorasan (index number = 10).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{10-1}	0	60033.5	107377.6	0	0	0	0	0	0	0
D_{10-2}	0	42109.88	1,631,226	0	0	0	0	0	0	0
D_{10-3}	0	15438.55	1285.008	0	0	0	0	0	0	0
D_{10-4}	0	25807.83	19,558,812	0	0	0	0	0	0	0
D_{10-5}	0	34584.82	208037.2	0	0	0	0	0	0	0
D_{10-6}	0	757086.5	2,210,923	0	0	0	0	0	0	0
D_{10-7}	0	1,133,390	4,726,857	0	0	0	0	0	0	0
D_{10-8}	0	297340.5	7,185,420	0	0	0	0	0	0	0
D_{10-9}	0	0	704830.4	0	0	0	0	0	0	0
D_{10-10}	0	477799.2	2,855,039	0	0	0	0	0	0	0
D_{10-11}	0	2,659,667	9566.875	0	0	0	0	0	0	0
D_{10-12}	0	1,185,138	202616.2	0	0	0	0	0	0	0
D_{10-13}	0	2,145,993	1230.04	0	0	0	0	0	0	0
D_{10-14}	0	3,741,917	170353.3	0	0	0	0	0	0	0
D_{10-15}	0	363045.7	611.2792	0	0	0	0	0	0	0
D_{10-16}	0	11,397,459	11,736,239	0	0	0	0	0	0	0
D_{10-17}	0	138526.6	27644.04	0	0	0	0	0	0	0
D_{10-18}	0	2,480,824	361056.7	0	0	0	0	0	0	0
D_{10-19}	0	2,538,140	0	0	0	0	0	0	0	0
D_{10-20}	0	21218.99	5025.525	0	0	0	0	0	0	0
D_{10-21}	0	6,884,524	12,684,529	0	0	0	0	0	0	0
D_{10-22}	0	0	78708.1	0	0	0	0	0	0	0
D_{10-23}	0	959.8465	1,780,502	0	0	0	0	0	0	0
D_{10-24}	0	622465.4	6109.299	0	0	0	0	0	0	0
D_{10-25}	0	339.3379	6,733,580	0	0	0	0	0	0	0
D_{10-26}	0	2,529,456	1,541,370	0	0	0	0	0	0	0
D_{10-27}	0	1,869,911	355.2674	0	0	0	0	0	0	0
D_{10-28}	0	831734.3	0	0	0	0	0	0	0	0
D_{10-29}	0	3,774,254	2,593,215	0	0	0	0	0	0	0
D_{10-30}	0	1,296,172	25852.11	0	0	0	0	0	0	0
D_{10-31}	0	1,357,251	784601.1	0	0	0	0	0	0	0

Table K
The amount of bioethanol delivered to demand nodes from Semnan (index number = 15).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{15-1}	0	4,305,629	0	918368.7	0	8,796,588	0	0	26923.24	0
D_{15-2}	0	8,267,148	0	0	0	8,981,604	424806.2	162,762	67387.9	0
D_{15-3}	0	17780.4	0	0	0	204021.3	1,171,079	1,122,087	249568.9	0
D_{15-4}	0	3,429,984	0	17,555,632	0	20,831,525	2,407,328	1952.313	1,059,455	0
D_{15-5}	0	3,111,606	0	4,768,143	0	9,906,618	9,202,126	6,000,599	2,975,194	0
D_{15-6}	0	0	0	2,169,283	0	953.6914	2,426,680	1,135,688	112413.6	0
D_{15-7}	0	1,508,322	0	2325.725	0	9914.383	16144.03	17256.83	4,526,276	0
D_{15-8}	0	169438.2	0	0	0	4,668,964	1,482,900	34,013,447	3,837,407	0
D_{15-9}	0	3,525,369	0	1,310,423	0	2136.028	31158.1	9416.9	2,455,175	0
D_{15-10}	0	306,033	0	864706.4	0	0	2,224,318	0	1,650,361	0
D_{15-11}	0	332975.6	0	51172.61	0	884907.7	580130.6	2,430,144	37608.17	0
D_{15-12}	0	2,431,896	0	0	0	0	0	11138.41	3,160,451	0
D_{15-13}	0	4486.055	0	240636.2	0	256800.1	1167.285	828889.9	550,642	0
D_{15-14}	0	874530.1	0	4939.265	0	485402.7	1,311,845	0	1,728,343	0
D_{15-15}	0	68531.85	0	173751.5	0	138,188	696257.9	1,019,833	2,104,352	0
D_{15-16}	0	646.8553	0	5,628,952	0	5,324,813	8,375,663	4384.095	10,943,000	0
D_{15-17}	0	50494.08	0	352907.7	0	246665.6	273633.7	11,647,109	10,977,702	0
D_{15-18}	0	1,932,009	0	951,551	0	2,336,072	83296.8	94994.05	3,258,684	0
D_{15-19}	0	665.3288	0	5,067,059	0	1861.826	3,183,984	22396.86	0	0
D_{15-20}	0	6,930,596	0	415.3759	0	407.4256	5,603,039	465894.9	43939.79	0
D_{15-21}	0	418.1072	0	5817.706	0	2308.644	4,752,793	190,267	4,994,223	0
D_{15-22}	0	1,135,150	0	3360.605	0	0	4,155,961	381221.6	183814.4	0
D_{15-23}	0	741292.9	0	1361.236	0	1,312,916	39135.17	39368.2	2806.423	0
D_{15-24}	0	208796.5	0	7,685,344	0	3,335,046	1,512,328	0	866631.4	0
D_{15-25}	0	4913.022	0	2,577,813	0	6,209,705	9,596,387	164943.9	0	0
D_{15-26}	0	26817.84	0	3,301,553	0	591.3887	4,271,783	121743.8	2,489,140	0
D_{15-27}	0	12,449,069	0	60130.58	0	12176.87	169549.5	4292.736	14,306,486	0
D_{15-28}	0	0	0	3,313,546	0	11024.93	5677.205	100.7864	1,465,421	0
D_{15-29}	0	1,008,429	0	747372.3	0	4,776,651	1357.679	164558.4	3,983,266	0
D_{15-30}	0	0	0	2,008,444	0	4,195,453	0	7,061,795	13807.64	0
D_{15-31}	0	240378.8	0	2688.195	0	3,257,072	1,514,517	0	1445.352	0

Table L
The amount of bioethanol delivered to demand nodes from Golestan (index number = 24).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{24-1}	0	0	0	0	0	0	0	0	0	9,105,199
D_{24-2}	0	0	0	0	0	0	0	0	0	5830.621
D_{24-3}	0	0	0	0	0	0	0	0	0	0
D_{24-4}	0	0	0	0	0	0	0	0	0	7,915,483
D_{24-5}	0	0	0	0	0	0	0	0	0	6,890,930
D_{24-6}	0	0	0	0	0	0	0	0	0	111221.7
D_{24-7}	0	0	0	0	0	0	0	0	0	384835.5
D_{24-8}	0	0	0	0	0	0	0	0	0	9160.388
D_{24-9}	0	0	0	0	0	0	0	0	0	1,528,863
D_{24-10}	0	0	0	0	0	0	0	0	0	0
D_{24-11}	0	0	0	0	0	0	0	0	0	12,350,635
D_{24-12}	0	0	0	0	0	0	0	0	0	2,726,381
D_{24-13}	0	0	0	0	0	0	0	0	0	8,521,335
D_{24-14}	0	0	0	0	0	0	0	0	0	3,571,963
D_{24-15}	0	0	0	0	0	0	0	0	0	38773.2
D_{24-16}	0	0	0	0	0	0	0	0	0	99096.29
D_{24-17}	0	0	0	0	0	0	0	0	0	230765.2
D_{24-18}	0	0	0	0	0	0	0	0	0	62639.6
D_{24-19}	0	0	0	0	0	0	0	0	0	2187.941
D_{24-20}	0	0	0	0	0	0	0	0	0	1815.878
D_{24-21}	0	0	0	0	0	0	0	0	0	0
D_{24-22}	0	0	0	0	0	0	0	0	0	2,274,682
D_{24-23}	0	0	0	0	0	0	0	0	0	343,730
D_{24-24}	0	0	0	0	0	0	0	0	0	4,048,810
D_{24-25}	0	0	0	0	0	0	0	0	0	38772.49
D_{24-26}	0	0	0	0	0	0	0	0	0	0
D_{24-27}	0	0	0	0	0	0	0	0	0	11,647,853
D_{24-28}	0	0	0	0	0	0	0	0	0	0
D_{24-29}	0	0	0	0	0	0	0	0	0	1,895,815
D_{24-30}	0	0	0	0	0	0	0	0	0	180838.9
D_{24-31}	0	0	0	0	0	0	0	0	0	0

Table M
The amount of bioethanol delivered to demand nodes from Lorestan (index number = 26).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{26-1}	476776.6	0	0	0	0	0	0	0	0	0
D_{26-2}	10,069,333	0	0	0	0	0	0	0	0	0
D_{26-3}	256807.5	0	0	0	0	0	0	0	0	0
D_{26-4}	0	0	0	0	0	0	0	0	0	0
D_{26-5}	9,534,596	0	0	0	0	0	0	0	0	0
D_{26-6}	305547.4	0	0	0	0	0	0	0	0	0
D_{26-7}	593087.2	0	0	0	0	0	0	0	0	0
D_{26-8}	34,176,867	0	0	0	0	0	0	0	0	0
D_{26-9}	181637.9	0	0	0	0	0	0	0	0	0
D_{26-10}	3,180,800	0	0	0	0	0	0	0	0	0
D_{26-11}	0	0	0	0	0	0	0	0	0	0
D_{26-12}	668.8438	0	0	0	0	0	0	0	0	0
D_{26-13}	921711.9	0	0	0	0	0	0	0	0	0
D_{26-14}	82668.26	0	0	0	0	0	0	0	0	0
D_{26-15}	185687.9	0	0	0	0	0	0	0	0	0
D_{26-16}	1,030,049	0	0	0	0	0	0	0	0	0
D_{26-17}	268,112	0	0	0	0	0	0	0	0	0
D_{26-18}	4,374,515	0	0	0	0	0	0	0	0	0
D_{26-19}	0	0	0	0	0	0	0	0	0	0
D_{26-20}	223029.5	0	0	0	0	0	0	0	0	0
D_{26-21}	11,846,550	0	0	0	0	0	0	0	0	0
D_{26-22}	2,084,286	0	0	0	0	0	0	0	0	0
D_{26-23}	2,387,634	0	0	0	0	0	0	0	0	0
D_{26-24}	28030.76	0	0	0	0	0	0	0	0	0
D_{26-25}	5,699,090	0	0	0	0	0	0	0	0	0
D_{26-26}	1,968,505	0	0	0	0	0	0	0	0	0
D_{26-27}	9407.014	0	0	0	0	0	0	0	0	0
D_{26-28}	2621.187	0	0	0	0	0	0	0	0	0
D_{26-29}	1068.86	0	0	0	0	0	0	0	0	0
D_{26-30}	289757.1	0	0	0	0	0	0	0	0	0
D_{26-31}	202072.1	0	0	0	0	0	0	0	0	0

Table N
The amount of bioethanol delivered to demand nodes from Markazi (index number = 28).

Variable	Sol. 1	Sol. 2	Sol. 3	Sol. 4	Sol. 5	Sol. 6	Sol. 7	Sol. 8	Sol. 9	Sol. 10
D_{28-1}	930570.3	523020.9	10,862,406	438304.2	2,147,856	974187.1	2,504,840	9,449,103	8,023,927	3,172,122
D_{28-2}	863098.9	2,407,010	2975.116	579133.3	9318.693	11042.97	0	30244.71	8,905,388	1,542,289
D_{28-3}	4,550,258	3276.993	4,233,119	584.1153	64074.87	5352.667	199361.3	118322.4	5,089,628	771928.3
D_{28-4}	35731.9	18,794,224	201603.3	112453.3	2,725,219	1,351,889	169,094	154829.7	365219.5	11,420,391
D_{28-5}	313702.6	2,190,507	1,706,582	5,438,308	0	0	1,405,489	353197.1	0	4,836,110
D_{28-6}	103603.3	374431.7	196693.2	11410.1	5099.174	536054.7	0	52892.61	0	1,278,061
D_{28-7}	0	321743.6	268419.4	2,955,668	1,015,705	1,901,647	579950.5	4,472,395	391.4773	2,581,279
D_{28-8}	5,161,016	7,105,086	29,257,638	31,658,447	196182.3	11042.59	57926.45	19,799,215	3,500,188	6,538,298
D_{28-9}	1047.676	8867.562	1,801,487	821792.1	2803.928	0	220628.7	3,141,551	1,526,004	323.656
D_{28-10}	90601.02	1,872,961	81949.04	292216.6	32643.32	68225.82	677282.5	2,238,997	7839.557	450712.3
D_{28-11}	23,356,352	16,628,730	619.6566	10,030,658	12,585,395	25,958,679	17,088,408	13984.84	109866.8	1,488,961
D_{28-12}	2,552,074	182702.2	472.531	3,529,964	0	1143.682	2,279,634	0	568383.4	163254.1
D_{28-13}	296270.7	204541.3	481865.1	19,418,284	9,173,401	6,721,177	276942.5	19,660,477	75032.58	4,389,566
D_{28-14}	2,369,473	0	158461.2	227901.4	23582.73	459766.5	2,084,378	768308.8	769098.2	0
D_{28-15}	2,362,621	2,520,976	19273.76	290159.2	1,300,815	0	1,063,076	1,999,486	0	280722.2
D_{28-16}	4,878,006	393.1974	83596.83	398790.5	20589.39	0	5624.364	6,410,910	0	10,212,309
D_{28-17}	0	0	109070.5	22497.94	887276.5	648342.6	15,385,586	178.8279	108,551	83.30102
D_{28-18}	3192.317	51117.09	3,956,972	0	900522.1	1010.721	2,248,967	364,410	1,021,235	5,109,994
D_{28-19}	749073.3	258183.1	3,653,859	0	1,063,634	0	848.4067	63020.66	0	6922.829
D_{28-20}	3,483,721	60133.34	634.8511	2,369,705	566.398	993177.5	804.3009	0	5,256,751	426997.1
D_{28-21}	2,030,121	204.1494	132712.6	0	13,063,124	41459.84	5,476,206	132527.3	8,232,129	0
D_{28-22}	125206.6	7,381,937	533044.1	920.1338	515094.3	3,330,063	2,195,866	861811.7	4,763,975	4,474,987
D_{28-23}	3057.161	854409.6	558085.1	0	0	73012.51	498,814	0	0	310901.8
D_{28-24}	179158.6	2,530,239	2,507,442	85217.85	565464.7	14300.21	0	3,187,549	5,828,628	419892.4
D_{28-25}	85368.27	1,532,156	2,507,691	6,478,116	1,396,460	985655.7	252789.5	0	42746.33	215589.8
D_{28-26}	349599.2	252021.6	2,116,310	0	1,864,916	2,841,861	0	14671.04	1,663,618	1,248,679
D_{28-27}	14,425,765	84326.03	0	24350.36	581549.7	550142.4	14,205,330	0	0	4462.819
D_{28-28}	259207.3	421,271	2,227,904	1,870,909	0	5,398,052	1,506,589	6,183,740	102550.9	4,740,985
D_{28-29}	321036.4	426213.5	4,971,737	118995.5	4,895,916	12548.03	4,899,132	0	570.2276	76958.77
D_{28-30}	3784.242	6,178,234	589.5318	149095.6	81497.89	333517.2	960867.4	14911.73	5,055,524	37751.65
D_{28-31}	636353.4	662287.5	516867.3	0	1,090,255	116264.1	426.8159	4,734,852	149242.1	11441.54

$$\sum_{j=1}^{n} w_j = 1$$

$$w_j \geq 0, \quad \text{for all } j \tag{2}$$

Considering the result of Model 2 both the local weight of criteria presented in Fig. 3 and (ξ^*) are calculated. We used input-based consistency ratio (CR) and the associated thresholds (Liang et al., 2020) to check the consistency of the pairwise comparisons, and we found all acceptable. To have the global weight of criteria, we multiply the local weight of criterion by ones belong to each branch of the hierarchical tree.

Table A
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