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A Bi-Objective Vehicle-Routing Problem for Optimization of a Bioenergy Supply Chain by Using NSGA-II Algorithm

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Abstract *– In this paper, we develop a multi-period mathematical model involving economic and environmental considerations. A vehicle-routing problem is considered an essential matter due to decreasing the routing cost, especially in the concerned bioenergy supply chain. A few of the optimization model recognized the vehicle routing to design the bioenergy supply chain. In this study, a bi-objective mixed-integer linear programming (MILP) model is presented. The economic objective function minimizes the transportation, capacity expanding, fixed and variable costs, and the locating routing cost in this problem. The proposed bi-objective model is solved through a Non-Dominated Genetic Algorithm (NSGA- II). Furthermore, the small-sized problem is solved by the CPLEX solver and augmented ε-constraint method.*

Keywords*– Bi-objective optimization; Mixed-integer linear programming; Bioenergy supply chain; Non-dominated genetic algorithm (NSGA- II).*

I. INTRODUCTION

Nowadays, fossil fuels are considered the primary energy sources, which include high percentages of carbon, petroleum, coal, and natural gas (Keeling, C. D, 1973). However, increasing the energy demand in conjunction with considering the environmental impacts of conventional energy consumption has resulted in a growing share of renewable energy in the energy supply chain. Therefore, countries worldwide are tending to utilize renewable energy like bioenergy instead of fossil fuels. Bioenergy can be generated from various sources comprising residues jatropha, switchgrass, and agriculture residues, which can be cultivated or collected from various sites (Chambost & Stuar, 2007, Iakovou et al., 2010, Ćosić et al., 2011)

It is necessary to focus on environmental consideration in a comprehensive bioenergy supply chain to decrease greenhouse gas (GHG) emissions. Reducing GHG emissions may improve ecosystem quality. Using a vehicle-routing problem in the bioenergy supply chain can improve environmental conditions.

A significant matter in the electricity market is capacity expansion (Ochoa & Van Ackere, 2009). Also, concerning ecosystem conditions, it can mitigate the removal whole of biomass due to expanding the capacity of biomass centers. With the capacity expansion strategy, resource plans can be prepared through organizations. Indeed, 20 to 30-year horizon resource investment plans can be prepared by using this strategy, and a long-term reliable condition can occur. The capacity expansion strategy incorporates data such as fuel, size, location, and timing of capital projects.

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In recent years, lots of research about biomass production and conversion processes has investigated the importance of logistics. Quantitative models can investigate the required resources, costs, energy consumptions, and the environmental impacts—for example, a model proposed by Ba et al. (2016). A programming model proposed by Zhu et al. (2011) considered planting and harvesting of biomass crops to deliver into bio-refinery. The residue handling, strategic decisions in the supply chain design, and tactical decision on the yearly operation schedules are examined in this model. The profit of bioenergy can be increased through mass production with a stable biomass supply. In the bioenergy supply chain, many optimization models have been proposed which address economic criteria and tried to maximize the total profit (Yue et al., (2014)). For example, the model proposed by Heydari and Askarzadeh (2016) optimized the power plant size for meeting the electrical power demand. On the other hand, the reliable and cost-effective hybrid energy system can be made by the combination of photovoltaic and biomass systems in the biomass supply chain developed by Woo et al.(2016).

First of all, the economic objective function minimizes total costs for a comprehensive biomass-to-hydrogen supply chain. In the strategic design of the biodiesel supply chain network proposed by Babazadeh et al. (2015), the economic objective aimed to minimize the total cost, including fixed opening costs, production cost, inventory holding cost, transportation cost, and importing costs. The supply chain is investigated from a broader perspective, involving environmental targets (Čuček et al., 2011; Santibañez et al., 2011; Cambero et al., 2016). The model proposed by Babazadeh et al. (2017) aims to minimize the supply chain costs from feedstock supply zone to customer centers. Also, minimizing the environmental impact (EI) is considered. It is demonstrated that high expenses are necessary for enhancing the environmental impact and also, it is vital for the risk of sustainable biodiesel supply chain network design. Marufuzzaman et al. (2014) developed a model intending to minimize the total costs.

Biofuels and bioenergy can be used to reduce fossil fuels, consumptions, and GHG emissions. Forestry-based biomass supply chain for heating energy is proposed by Paolotti et al. (2015). Rabbani et al. (2018) proposed a sustainable bioenergy supply chain considering economic, environmental, and social objective functions. Furthermore, Rabbani et al. (2020) developed a multi-objective mixed-integer linear programming model with a solution approach incorporating Best-Worst Method (BWM) approach in an augmented ε-constraint method to design a sustainable sewage-based bioethanol supply chain. Table I summarizes the remarkable features of the studies mentioned above and current work.

TABLE I. FEATURES of THIS SUPPLY CHAIN PROBLEM.

Study	***Cost components***				***Capacity expansion***	***Solution***			
	Fixed cost	***Operating cost***	***Storage cost***	***Routing cost***		***Others***	***CPLEX***	***Meta-heuristic***	***Augmented ε-constraint***
Marufuzzaman et al.(2014)	*	*				*			
Cobuloglu and Büyüktahtakın (2014)	*					*			
Paulo et al. (2015)	*	*					*		
Claudia et al. (2015)	*		*						*
Babazadeh et al. (2015)	*	*	*		*				*
Heydari and Askarzadeh (2016)	*	*				*			
Cambero and Sowlati (2016)	*	*							*
Rabbani et al. (2018)	*	*	*		*				*
Rabbani et al. (2020)	*	*							*
This study	*	*	*	*	*			*	

As can be found from our literature review, some features that distinguish this study from previous works are as follows:

- Incorporating the capacity expansion strategy is the underlying feature of this proposed supply chain network.
- Involving the vehicle-routing problem for biomass transportation and considering the routing cost besides the other costs.
- Considering environmental consideration as a second objective function.
- Developing a new bi-objective mathematical programming model.
- Applying the Non-dominated Sorting Genetic Algorithm (NSGA-II) to solve the model.

None of the recent research optimized a biofuel supply chain incorporating vehicle-routing- related decisions besides other strategic and tactical decisions to the best of our knowledge. Therefore, this paper suggests a bi-objective mathematical model design a bioenergy supply chain. The economic objective function minimizes total costs. Besides, the environmental objective function minimized the total GHG emission in the entire supply chain resulting from transportation, inventory holding, and facility establishment.

The rest of this paper is structured as follows: in Section 2 and 3, the model and problem are described. In Section 4, the solution method is presented. Numerical results are described in section 5, and finally, the concluding remarks are given in section 6.

II. PROBLEM DESCRIPTION

The schematic structure of the bioenergy supply chain is illustrated in Fig. 1. As seen in Fig. 1, the proposed supply chain includes the three levels, such as biomass feedstock center, a power plant generating electricity, and demand centers. The dotted arrows in this figure illustrate the routing of the transported biomass with the corresponding vehicle. In addition, in this study, the routing between biomass center plants has been investigated. The routes of the vehicles among the biomass center and power plants are solved differently for each period. Overall, the development of biomass supply chain for bioenergy plants considers several imperative processes: shipping raw material from biomass center to plants and then transporting the products from plant to demand center.

We supposed that the biomass supply center capacities could be expanded concerning increasing demand. That is, the capacity expansion strategy can be applied to this problem. However, it is not allowed for other facility capacities to be changed. The following assumptions are utilized to develop the proposed supply chain, network model:

There are two types of decisions: 1) Strategic decisions, including locating biomass centers and power plants with capacity levels, and allocating biomass feedstock to power plants. 2) Operational decision comprising determining the routes of vehicles to transport biomass feedstock. This model aims to specify the amount of capacity expansion for biomass center due to an increase of demand, the total capacity of each location considered to store the extra biomass, and the amount of biomass that can be stored at biomass center at each period as well. Also, an optimal location and capacity for installing the future power plant, amount of each biomass shipped to each facility, amount of generated product in the power plant that served to market, and finally, and amount of biomass gathered in each location each time could be determined.

III. MODEL FORMULATION

The purpose of this bi-objective mathematical model developed for designing the bioenergy supply chain is to minimize economic and environmental objective functions simultaneously. To formulate concerned bioenergy supply chain, the sets, parameters, and variables used are given below.

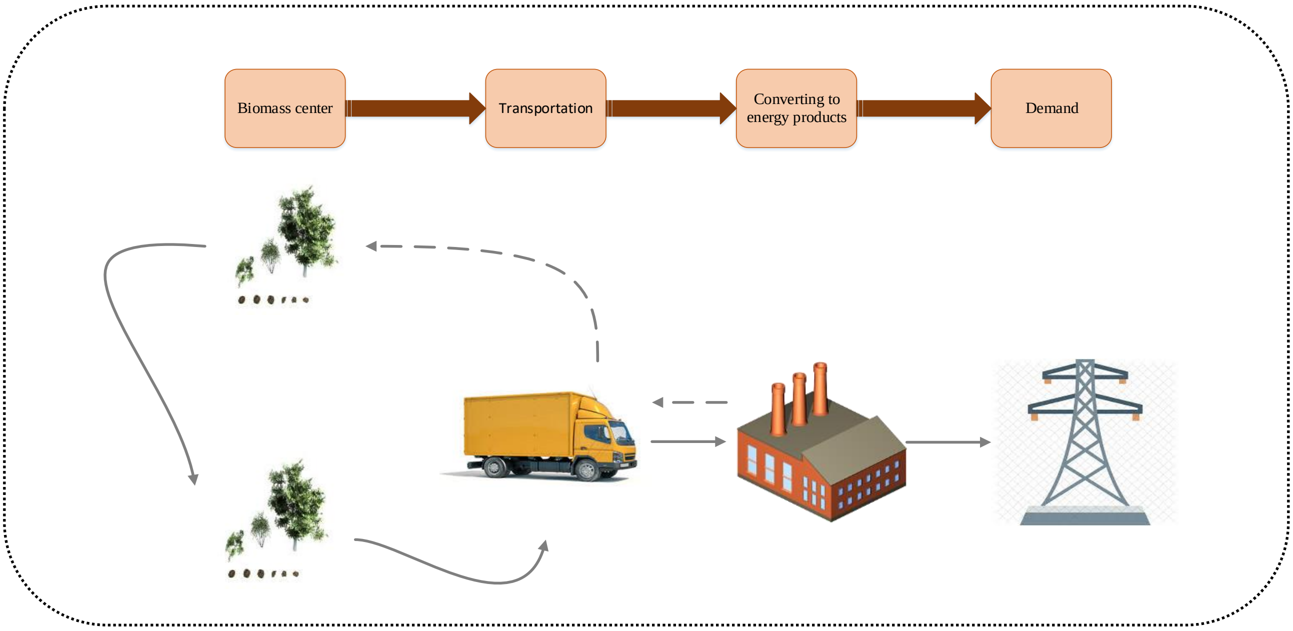

Fig. 1. A proposed network for the vehicle-routing problem of the bioenergy supply chain.

Sets

I Set of biomass center; index$i, m \in I$

J Set of candidate location for power plants; index $j \in J$

E Set of power plants capacity; index $e \in E$

R Set of vehicles; index $r \in R$

F Set of energy products type; index $f \in F$

V Set of demand zones; index $v \in V$

T Periods; index $t \in T$

Coefficient

UP_i^C Upper bound of biomass center capacity at location i

LW_i^C Lower bound of biomass center capacity at location i

ψ_{it} Amount of available biomass at location i at time t

M Big number

DS_{ij}	Distance between center i and plant location j
DS_{jv}	Distance between plant j and center v
DP_{fvt}	Maximum demand for product f in center v at time t
φ_e	The capacity of power plant e
ϑ_{ft}	Product Demand f at time t
ω_f	The conversion factor of biomass to product f
NB	The number of biomass centers (sub-tour constraint)

Economic coefficient

d_{im}	Unitary cost to transport between the centers i and m.
P_{fet}	The production cost of product f at a plant with capacity e at time t
C_{it}	Cost of acquisition 1 ton of biomass at location i at time t
IC_{je}	Investing cost of a plant with capacity e at location j
μ_{ij}	The maximum distance between a biomass center i and power plant location j
μ_{jv}	The maximum distance between a plant location j and a demand center v
fp_{et}	Fixed cost of operating plant with capacity j at time t
ρ_{ijrt}	Unit Cost of shipping between biomass center i and plant location j with vehicle r at time t
ρ_{jvt}	Transporting cost between plant j and demand v at time t
EC_{it}	The variable cost of biomass center capacity expa i at time t
ICB_{it}	The storage cost of biomass at center i at time t

Environmental coefficient

e	GHG emission of inventory holding of biomass at biomass center
e_{je}	GHG emission of installing plants j with capacity e
τ_{ijr}^{Tr}	GHG emission of shipping per unit of biomass from location i to location j with vehicle r

Continuous non-negative decision variables

B_{it} Amount of biomass collected at biomass center i in each period t

W_{ijrt} Amount of biomass transported from biomass center i to power plant j by vehicle r at time t

U_{fjevt} Amount of products type f transported from power plant j to market v at time t

I_{it}^{B} Stored biomass at biomass center i at time t

CE_{it} biomass center capacity i at time t

CEP_{it} biomass center capacity expansion i at time t

H_{ijrt} An auxiliary variable used for sub-tour elimination in the route of vehicle r in period t

Binary variables

X_{je} 1 if location j is selected for opening power plant with capacity e

Y_{fjv} 1 if a produced product type f is transported from power plant at location j to market v

Z_{ij} 1 if the amount of biomass is transported from biomass center i to the power plant j

R_{imjrt}^{rout} 1 if the vehicle by vehicle r belong to power plant j is traveled from biomass center i to biomass center m at time t (if i precedes m)

A. *Economic objective function*

The first objective function represents the minimization of the total costs, which consists of different types of cost that are summarized below:

- opening costs
- costs of transportation
- Acquisition costs
- Production costs
- Capacity expanding costs
- Storing costs
- Annual routing costs

Equation (1) is related to the estimation of fixed opening costs for installing a new power plant.

$$\sum_{j\epsilon J}\sum_{e\epsilon E} X_{je} IC_{je} \tag{1}$$

The transportation costs are presented in Eqs. (2) and (3). In Eq. (2), by multiplying transporting biomass flow, the distance between biomass center i and plant (DS_{ij}), and the unit transportation cost of biomass from biomass center i and power plant at location j (P_{ijrt}), biomass transportation costs can be calculated

The transportation costs of the product at the plant are calculated in Eq. (3). The annualized infrastructure cost for each product to satisfy the markets is considered. The unitary transportation cost is represented by P_{jvt} when electricity and product f goes from plant J to center v by establishing a grid and substation. The existence of the grid and substation is specified through a binary variable Y_{fjv}.

$$\sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{t\epsilon T} W_{ijrt} DS_{ij} P_{ijrt} \tag{2}$$

$$\sum_{f\epsilon F}\sum_{j\epsilon J}\sum_{v\epsilon V} Y_{fjv} DS_{jv} P_{jvt} \tag{3}$$

The total purchasing cost is estimated regarding the amount of biomass gathered on center i at time t (B_{it}) and the cost of acquisition biomass at biomass center i (Equation (4)).

$$\sum_{i\epsilon I}\sum_{t\epsilon T} B_{it} C_{it} \tag{4}$$

The production costs, which consist of variable and fixed operating costs, are calculated in Eqs. (5) and (6).

$$\sum_{f\epsilon F}\sum_{e\epsilon E}\sum_{j\epsilon J}\sum_{v\epsilon V}\sum_{t\epsilon T} P_{fet}\, U_{fjevt} \tag{5}$$

$$\sum_{q\epsilon Q}\sum_{e\epsilon E}\sum_{t\epsilon T} X_{qe} FP_{et} \tag{6}$$

As seen in Eq. (7), by multiplying the stored biomass j (I_{jt}^{B}) and the unit holding cost of the biomass (ICB_{jt}), storing cost is calculated. Additionally, the variable cost associated with the capacity expansion of biomass center is calculated in Eq. (8) by multiplying the capacity of biomass center i at time t (CE_{it}: when increasing the capacity of biomass is occurred) and variable cost per unit capacity of biomass center i at time $t(EC_{it})$.

$$\sum_{i\epsilon I}\sum_{t\epsilon T} ICB_{it} \times I_{it}^{B} \tag{7}$$

$$\sum_{i\epsilon I}\sum_{t\epsilon T} EC_{it} CE_{it} \tag{8}$$

Annual routing cost enables products to be transported directly from biomass center to their primary assignment. Equation (9) calculate this cost by multiplying the unitary cost to ship between the two nodes i and m and a binary variable R_{imjrt}^{rout} .

$$\sum_{i\epsilon I}\sum_{m\epsilon M}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{t\epsilon T} d_{im}\, R_{imjrt}^{rout} \tag{9}$$

Eventually, the objective function can be described as Eq. (10).

$$Minimize\ Z_1 = \sum_{j\epsilon J}\sum_{e\epsilon E} X_{je}IC_{je} + \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{t\epsilon T} W_{ijrt}DS_{ij}P_{ijrt} + \sum_{f\epsilon F}\sum_{j\epsilon J}\sum_{v\epsilon V} Y_{fjv}DS_{jv}P_{jvt} \\ + \sum_{i\epsilon I}\sum_{t\epsilon T} B_{it}C_{it} + \sum_{f\epsilon F}\sum_{e\epsilon E}\sum_{j\epsilon J}\sum_{v\epsilon V}\sum_{t\epsilon T} P_{fet}\,U_{fjevt} + \sum_{q\epsilon Q}\sum_{e\epsilon E}\sum_{t\epsilon T} X_{qe}FP_{et} \\ + \sum_{i\epsilon I}\sum_{t\epsilon T} ICB_{it} \times I_{it}^{B} + \sum_{i\epsilon I}\sum_{t\epsilon T} EC_{it}CE_{it} + \sum_{i\epsilon I}\sum_{m\epsilon M}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{t\epsilon T} d_{im}\,R_{imjrt}^{rout} \tag{10}$$

B. Environmental objective function

GHG emissions resulted from activities from biomass center to demand center are minimized in this problem.

$$Minimize\ Z_2 = \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{r\epsilon R}\sum_{t\epsilon T} \tau_{ijr}^{Tr} \times W_{ijrt} + \sum_{i\epsilon I}\sum_{t\epsilon T} e\,I_{it}^{B} + \sum_{j\epsilon J}\sum_{e\epsilon E} e_{je}X_{je} \tag{11}$$

Equation (11) states GHG emission resulted from transporting materials between centers.

C. Model constraints

In the following, the feasible solution space is described:

$$B_{it} \le \psi_{it} \qquad \forall i \in I,\ \ \forall t \in T \tag{12}$$

$$\sum_{i\epsilon I}\sum_{r\epsilon R}\sum_{f\epsilon F} \omega_f\, W_{ijrt} = \sum_{f}\sum_{e}\sum_{v} U_{fjevt} \qquad \forall j \in J,\ \ \forall t \in T \tag{13}$$

$$\sum_{q\epsilon Q}\sum_{e\epsilon E}\sum_{v\epsilon V} U_{fqevt} = \vartheta_{ft} \qquad \forall f \in F,\ \ \forall t \in T \tag{14}$$

$$\sum_{j\epsilon J}\sum_{e\epsilon E} U_{fjevt} \le DB_{fvt} \qquad \forall f \in F,\ \ \forall v \in V,\ \ \forall t \in T \tag{15}$$

$$\sum_{f\epsilon F}\sum_{v\epsilon V} U_{fjevt} \le \varphi_e X_{je} \qquad \forall j \in J, \forall e \in E, \forall t \in T \tag{16}$$

$$\sum_{e\epsilon E} U_{fjevt} \le Y_{fjv}M \qquad \forall f \in F, j \in J,\ \ \forall v \in V, \forall t \in T \tag{17}$$

$$I_{it}^{B} = I_{i(t-1)}^{B} + B_{it} - \sum_{j\epsilon J}\sum_{j\epsilon J} W_{ijrt} \qquad \forall i \in I\ , \forall t \in T \tag{18}$$

$$CE_{it} = CE_{i(t-1)} + CEP_{it} \qquad \forall i \in I, \quad \forall t \in T \tag{19}$$

$$LW_i^C \le CE_{it} \le UP_i^C \qquad \forall i \in I, \quad \forall t \in T \tag{20}$$

$$I_{it}^B \le CE_{it} \qquad \forall i \in I, \ \forall t \in T \tag{21}$$

$$DJQ_{ij} \ge \mu_{ij} \ , W_{ijrt} = 0 \qquad \forall i \in I, \quad \forall j \in J \ , r \in R \ , \forall t \in T \tag{22}$$

$$DQV_{jv} \ge \mu_{jv} \ , U_{fjevt} = 0 \qquad \forall j \in J \ , \ \forall v \in V \tag{23}$$

$$\sum_{e \epsilon E} X_{je} \le 1 \qquad \forall j \in J \tag{24}$$

$$Z_{ij} \le \sum_{i \epsilon I} \sum_{j \epsilon J} W_{ijrt} \le M Z_{ij} \qquad \forall i \in I, \quad \forall j \in J \ , \forall t \in T \tag{25}$$

$$\sum_{m \epsilon M} \sum_{r \epsilon R} R_{imjrt}^{rout} = 1 \qquad \forall i \in I, \quad \forall j \in J, \forall t \in T \tag{26}$$

$$\sum_{i \epsilon I} \sum_{r \epsilon R} R_{imjrt}^{rout} \le 1 \qquad \forall m \in M, \quad \forall j \in J, \ \ \forall t \in T \tag{27}$$

$$\sum_{m} R_{imjrt}^{rout} - \sum_{m} R_{mijrt}^{rout} = 0 \qquad \forall i \in I, \quad \forall j \in J, \qquad \forall r \in R, \qquad \forall t \in T \tag{28}$$

$$H_{ijrt} + H_{mjrt} + |NB| R_{imjrt}^{rout} \le |NB| - 1 \qquad \forall i \in I, \quad \forall m \in M, \ \forall j \in J, \ \forall r \in R, \forall t \in T \tag{29}$$

Constraint (12) ensures that the total biomass is restricted concerning the maximum raw material at the biomass center i. Constraint (13) states that the sum of produced products flows (U_{fjevt}) must be equal to shipped biomass (W_{ijrt}) multiplied by a conversion factor of biomass to bioenergy (ω_f). Constraint (14) considers the bound for meeting the various kinds of products at time t. Constraint (15) indicates the allowable amount of product to the demand center. Constraint (16) sets the upper limit on the flows of biomass feedstock that enter a power plant to be converted to the product (U_{fqevt}). Constraint (17) indicates that a link to a grid and substation must be considered when a product f is produced. Constraint (18) guarantees that the summation of the amount of stored material $(I_{i(t-1)}^B)$ and the amount of biomass collected in that period minus the amount of raw material transported to plant is equal to the inventory of biomass feedstock at biomass center in each period. Constraints (19) and (20) state capacity expansion restriction by setting upper and lower bounds for biomass center. Constraint (21) restricts the stored biomass. Constraint (22) ensures that the biomass flows depend on the distance between the biomass zone and plants. Therefore, when the distance between biomass zone and plant is greater than μ_{ij} , the material is enforced to be (S_{ijrt}). Similarly, constraint (23) restricts the distance between plant j and demand zone v. Constraint (24) shows that installing one plant with capacity e at location j is allowed. Constraint (25) indicates that the routing between biomass zone and plant is guaranteed when the biomass feedstock amount is shipped between two nodes. Constraint (26) restricts the number of routes assigned for biomass center. Constraint (27) guarantees that each route comprises of one truck. Constraint (28) states that the exit of each vehicle from each node is only allowable after its entrance to them, and finally, constraint (29) states that the sub-tour each tour is allowed to start from a power plant and multiple biomass centers.

IV. SOLUTION APPROACH

The presented problem consists of two subproblems, including a location-routing problem and a transportation problem. Both location-routing and transportation problems are proven as NP-hard problems (Perl and Daskin., 1985). Therefore, to solve the presented problem, a fast and efficient solution method is needed. As the problem is a bi-objective optimization model, we apply a meta-heuristic approach to the problem. The non-dominated sorting genetic algorithm II (NSGA-II), presented by Deb et al. (2002), is utilized to deal with this problem.

The NSGA-II algorithm is a practical algorithm for searching solution space. This algorithm utilizes a "non-dominance approach" and a "crowding distance procedure" for ranking the Pareto front solutions.

For generating a new solution, crossover and mutation operators are applied. The better Pareto front from this solution will be obtained by combining the current population and the newly generated population and using the "non-dominance" and "crowding distance".

In the non-dominance procedure, all non-dominated solutions are put in the first Pareto front. Then, the second front includes the solutions dominated by the first Pareto front. We continued this procedure until we place all of the solutions on their fronts. After this procedure, to rank the non-dominated solutions, the algorithm uses the crowding distance measure in which the higher value of "crowding distance" brings about the greater "probability of selection".

A. Solution representation

The following arrays are utilized for representing the problem solution:

1) The number of vehicles array: an array with V number of cells is created, which V represents the number of vehicles available in the first stage. This array contains random permuted numbers from 1 to V. The place of the largest number shows the number of vehicles to be utilized. Fig. 2 demonstrates an instance of this array, which indicates that two vehicles should be used.

2	4	3	1

Fig. 2. The number of vehicles array with four vehicles.

2) Usage of vehicles array: an array with V number of cells is created, which V represents the number of vehicles available in the first stage. This array contains random permuted numbers from 1 to V. This array shows which vehicles should be utilized. Fig. 3 demonstrates an example of this array.

1	3	2	4

Fig. 3. Usage of vehicles array that shows the vehicles number 1 and 3 should be used.

3) Locating array: an array with V number of cells is created, which V represents the number of vehicles available in the first stage. Each cell contains the number of potential facilities to be located in the second stage. Fig. 4 shows an example of this array. In this figure, facilities 1 and 3 are located, and vehicle 1 is allocated to facility 3, and vehicle 3 is allocated to facility 1.

3	3	1	1

Fig. 4. Locating an array with 4 vehicles and 3 potential facilities.

4) Biomass tour and biomass sequence: two arrays with I number of cells is created, which I represents the number of biomass centers available in the first stage. These arrays contain random permuted numbers from 1 to I. The biomass tour array determines the number of biomass centers that each vehicle should serve, and the biomass sequence shows which biomass centers are allocated to each vehicle. Figs. 5 and 6 show examples of these arrays.

1	5	4	2	3

Fig.5. Biomass tour array for a network with 5 biomass centers.

In this array, one biomass center is allocated to the first vehicle, and the other four centers are allocated to the second vehicle (because we have 2 vehicles from the first array).

2	4	1	5	3

Fig. 6. Biomass sequence array for a network with 5 biomass centers.

In this array, the biomass center with the index of 2 is served by vehicle 1, and the biomass center with an index of 4, 1, 5, and 3 are served by vehicle 2.

5) Second stage array: an array with $J + R$ number of cells is created, which J represents the number of energy production facilities, and R represents the number of customers available in the second stage. This array contains random permuted numbers from 1 to $J + R$. To decode this array, we use priority-based decoding. In this decoding procedure, the highest number in the array is selected. If this number belongs to the facilities, the customer with minimum transportation cost is allocated to this facility. If this number belongs to the customers, the facility with minimum transportation cost is allocated to this customer. Then, according to the capacity of the facilities, the transportation flow is allocated. This procedure is continued until all of the demands are satisfied. This decoding method is described in detail in Roghanian and Pazhoheshfar (2014).

B. Genetic operators

The NSGA-II algorithm has three leading operators, which have a notable effect on the algorithms' efficiency. These operators are "parent selection operator", "crossover operator", and "mutation operator".

There are various selection approaches for parent's selection, such as "roulette wheel selection", “tournament selection”, “rank selection,” etc. In this paper, we use the roulette wheel selection.

For the crossover operator, we used the weight mapping crossover to keep the solution of each individual feasible. Also, three operators, as swap, reversion, and insertion, are utilized for mutation operators.

V. COMPUTATIONAL RESULTS

To conduct numerical experiments, we coded the mathematical programming model of the problem in the GAMS software. We used the mathematical model to solve with an exact method, which is the augmented ε-constraint method. Also, we coded the proposed NSGA-II meta-heuristic algorithm in the MATLAB software with a version of R2015a. All numerical experiments are conducted on a personal computer with a 2.5GHz Core i5 processor and 8 GB RAM.

A. Parameter tuning

At first, we performed parameter tuning for the proposed NSGA-II algorithm. Parameter tuning improves the search procedure of the algorithm. The number of generations, population size, crossover probability, and mutation probability are among the NSGA-II algorithm's parameters. To tune these parameters a Taguchi design of experiments is performed. In this method, we consider three levels for each parameter (low, medium, and high). We conduct a L^9 design in the Taguchi method, and for each parameter, we choose the level with the highest signal to noise (S/N) value. For the proposed meta-heuristic, we used 0.7 as the crossover probability, 0.2 as the mutation probability, 150 as the population size, and 400 for the number of generations.

B. Test problem generation

To test the proposed algorithm and to perform the computational experiments, we generated 10 test problems. The characteristics of these test problems are listed in Table II. To generate test problems, the parameters of the model are set by using a randomly generated uniform function.

TABLE II. CHARACTERISTIC OF TEST PROBLEMS.

Prob. No	$\|I\|$	$\|J\|$	$\|E\|$	$\|R\|$	$\|F\|$	$\|V\|$	$\|T\|$
1	2	2	1	3	2	4	2
2	2	2	1	3	2	4	2
3	2	3	1	4	2	4	2
4	3	3	1	5	2	5	2
5	3	4	2	5	3	6	2
6	4	4	2	6	3	6	3
7	4	5	2	6	3	8	3
8	4	5	2	6	4	9	3
9	5	6	3	7	4	9	4
10	5	7	3	7	4	10	4

C. Results

Table III provides the results obtained from solving each test problem using the NSGA-II meta-heuristic. In this table, the number of Pareto solutions (NOS), the best value obtained for each objective function and the CPU time in seconds are provided for each test problem. The number of Pareto solutions is a metric to show the efficiency of an algorithm. Also, the CPU time of solving the problem demonstrates the effectiveness of the meta-heuristic. Fig. 7 shows Pareto solutions to problem number 8; it shows the trade-off between both objective functions, decreasing the GHG emission is occurred due to an increase in the total costs (first objective function). Fig. 8 illustrates a comparison of NSGA-II and the ε-constraint method in terms of the CPU time. As can be seen, by increasing the CPU time, the solution time increases exponentially by using the augmented ε-constraint method. Therefore, for the large dimension of the problem, the NSGA- II algorithm outperforms the augmented ε-constraint method in terms of CPU time. Another important note regarding the computational results is that a marginal increase in total cost would lead to an 18% decrease in the GHG emission of the entire supply chain. So, managers and decision-makers could make an appropriate decision in designing such a supply chain.

TABLE III. RESULTS OF TEST PROBLEMS.

Prob. No	*NOS*	*OFV1*	*OFV2*	*CPU (s)*
1	5	98374412.43	2217891.94	22.13
2	4	309743596.79	2988692.32	22.81
3	4	206997545.04	3431288.64	22.95
4	5	352031656.95	4430113.56	25.43
5	7	961714973.87	8039178.61	34.60
6	12	1856801151.56	14275529.16	50.39
7	10	5929791080.03	43193618.73	65.61
8	10	8640264880.15	64929689.02	82.85
9	12	9513146239.58	75055192.81	123.56
10	14	9923263035.83	86580403.13	208.44

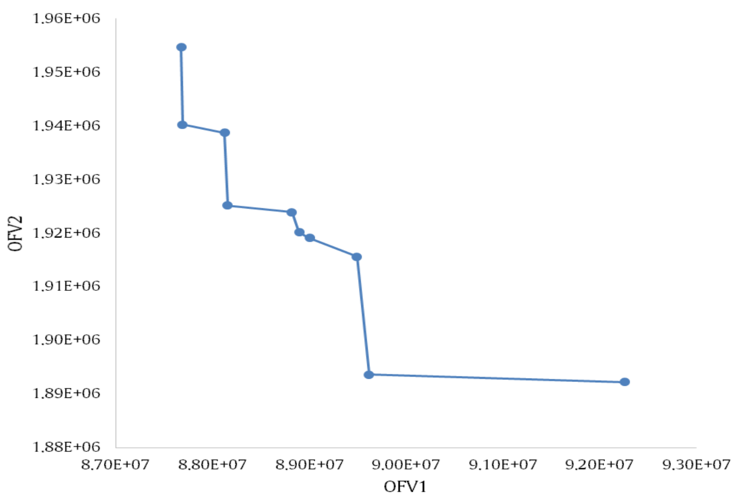

Fig. 7. Pareto solutions of the test problem No. 8

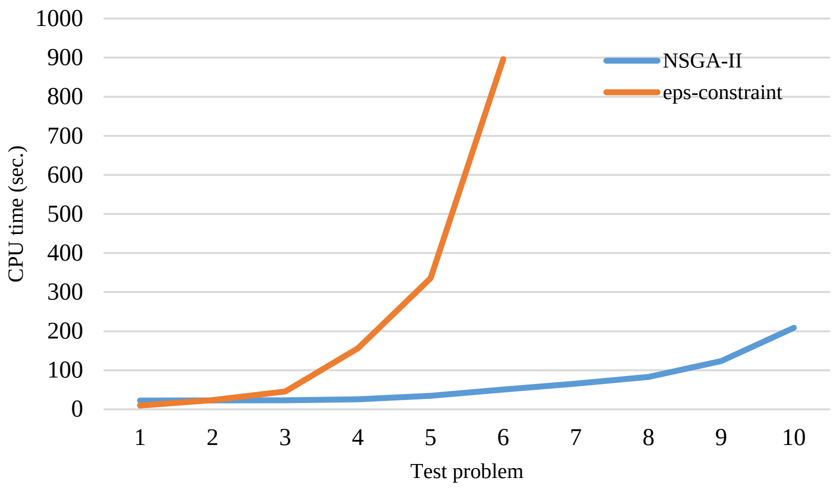

Fig. 8. Comparison of CPU times of two solution algorithms

VI. CONCLUSION

A vehicle-routing problem for optimization of a bioenergy supply chain planning was developed. Incorporating a vehicle-routing problem plays a role as an essential role due to the importance of decreasing GHG emissions. Minimizing the total costs and GHG emissions of the vehicles is the aim of this article. We proposed an effective multi-objective meta-heuristic for solving such a problem. The presented NSGA-II algorithm provided a Pareto-optimal set and had a good performance in the large-size instances. Besides, the obtained two objective functions were compared with each other, and the trade-off between these objectives has been analyzed. It was also concluded that the proposed model could play an essential role in deciding for decision-makers and practitioners for designing a bioenergy supply chain by considering economic and environmental criteria.

To provide future research, the authors suggest recommendations as follows: considering social impacts for environmental factors and providing other solution procedures.

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