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A multi-objective optimization model considering inventory strategy for biofuel supply chain design

Yong ZHANG[1, a], Rui ZHANG[1, b]
[1]School of Transportation, Southeast University, Nanjing, Jiangsu, 21096, China
[a]631407802@qq.com, [b]397635490@qq.com

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Abstract. Energy conservation and pollution reduction are two of important subjects of sustainable development. Straw recycling not only can achieve the maximization of resource utility, but also could reduce environmental pollution caused by straw burning. How to set up an efficient straw recycling network is of great significant. In this study, a multi-objective model that considering inventory strategy is developed for biofuel supply chain design. This optimization model has two objectives, one is to maximize the profit of the entire supply chain, and the other one is to minimize the total carbon emission. In order to solve the multi-objective model, we try to use the two-stage fuzzy method to transform the model to a single objective form. Finally, we use the MATLAB R2015b with YALMIP toolbox to for programming. The results reveal that this model can balance the two objectives well at the same time. Proper use of the model can help managers to design the biofuel supply chain.

Introduction

As the best alternative to traditional fuels, biofuels have attracted much attention all over the world. N. Gaurav et al. (2017) listed the advantages of biofuels over petroleum fuels: (a) they can be easily extracted from the biomass, (b) they are sustainable due to biodegradable property, (c) its combustion based on carbon-dioxide cycle, (d) more environment friendly. Jason Hill et al. (2006) gave the quantitative analyses of biofuels contrasted to petroleum. The results showed that biodiesel prepared from soybeans could reduce greenhouse gas emissions by 41% while bioethanol produced by corn reduces greenhouse gas emissions by 12%. In addition, biofuel could also substantially reduce the emissions of air pollutants like CO, SO_x, VOC, PM10, etc.

Although the production of biofuels has a good prospect of development, the industry is still in development for the time being. Influenced by many factors such as large investment, high cost and lack of industrialization, the biofuel industry is still faced with many bottlenecks in the commercialization process. In addition to technical difficulties, one of the bottlenecks is the supply chain coordination and optimization problem (Yunjian Jiang, 2016).

In this paper, a multi-objective model considering inventory strategy for biofuel supply chain design is developed. The model is aimed to maximize the profit of the supply chain and minimize the carbon emissions in transportation, production, inventory, etc.

The rest of this article proceeds as follows: Section 2 is dedicated to a review of literature. Section 3 present the problem formulation including problem description and assumptions, notation and model formulation. Section 4 proposes the solution method of solving the model. Section 5 shows the computational results of the model. Finally, conclusions are given in section 6.

Literature review

This section presents some prior research in the relevant field of biofuel, biofuel supply chain design, multi-objective optimization in supply chains.

Biofuel

At present, with the upgrading of biofuel production technology, Inderwildi et al. (2009) summarized that biofuels are mainly divided into four generations. The first-generation biofuels have higher requirements for raw materials, and their biofuel products are mainly used to drive engines. The second-generation biofuels rely on liquid technology for the conversion of solid biomass materials. The third-generation biofuels mainly used algae as raw materials, the technology has been developed but has not been used in commercial production. The second and third generation of biofuels not only get rid of the use of food crops, but also have a low price of raw materials, thus they have received widespread recognition. The fourth generation of biofuels has not yet been clearly defined and is still under study.

Biofuel supply chain design

Rentizelas et al. (2009) built a decision support system based on the research of biofuel conversion system with a variety of biomass materials, which could help decision-makers to make investment decisions. The expected goal of the system is to maximize the profit considering biomass materials, energy conversion facilities and air conditioning system, etc. Kang et al. (2010) built a multi period mixed integer linear programming model, the model was set in biofuel production system of Illinois, and focused on biofuel refinery location problem, conversion and transportation problem of biofuel products and by-products during production process. The results showed that the biofuel refineries should be built near the place of raw material so as to form scale effect. Khanna et al. (2010) established a mixed integer programming model, including two dimensions of time and space. The model was to handle the issue of three grade biofuel supply chain network which was composed of the places of biomass raw materials, biomass fuel refinery and the demand. It took eight kinds of raw materials into account, and aimed at minimizing the cost. The research results showed that the operating efficiency of the supply network was greatly improved and the cost of supply chain network was substantially reduced. Kim et al. (2011) constructed a mixed integer programming model considering the uncertainty of biomass fuel demand and generating stochastic scenarios on this basis. The model set the expected system profit maximization as its objective function and could deal with sales decision and refinery decision problem.

Multi-objective optimization in supply chains

Rong et al. (2011) developed a mixed integer linear programming model for solving a production and distribution planning problem of a food supply chain. Liu and Papageorgiou (2013) addressed issues in production, distribution and capacity planning of a global supply chain and developed a multi-objective mixed-integer linear programming approach in optimization of the total cost, the flow time and the loss of sales as three objectives. Harris et al. (2014) proposed a multi-objective optimization approach for solving a facility location–allocation problem of a supply chain network where financial costs and CO_2 emissions are considered as objectives. Sahar et al. (2014) proposed a multi-objective optimization model of a two-layer dairy supply chain aimed at minimizing the amount of CO_2 emissions for transportation and the total cost for the product distribution.

The literature review showed that several studies applied the multi-objective optimization approach to supply chains network design. But only few of models proposed in the current literature have considering inventory strategy in biofuel supply chain design. In addition, most multi-objective optimization models are solved by converting multi-objectives into a single one using efficacy factor α, which is highly subjective.

The main contributions of this article can be summarized as follows:

- It takes inventory strategy into account during the biofuel supply chain design;
- The background of the model is based on straw recycling network;
- The model has two objectives: one is to maximize the total profit and the other one is to minimize the carbon emissions;
- The solving method of the model is two-stage fuzzy method which could avoid subjective factors.

Problem formulation

Problem description and assumptions

The general structure of the proposed reverse logistic network is illustrated in Fig. 1. In forward direction, the suppliers (farms) are responsible for providing three kinds of biomass according to the month. The biomass is conveyed to customers the collection centers where the biomass is pretreated and then stored. Every month, the plant takes away a fixed quantity of pretreated biomass from the collection centers in total for production. The biofuel product is transported to the customers, including the fixed customers with fixed demand and external customers absorbing the rest biofuel.

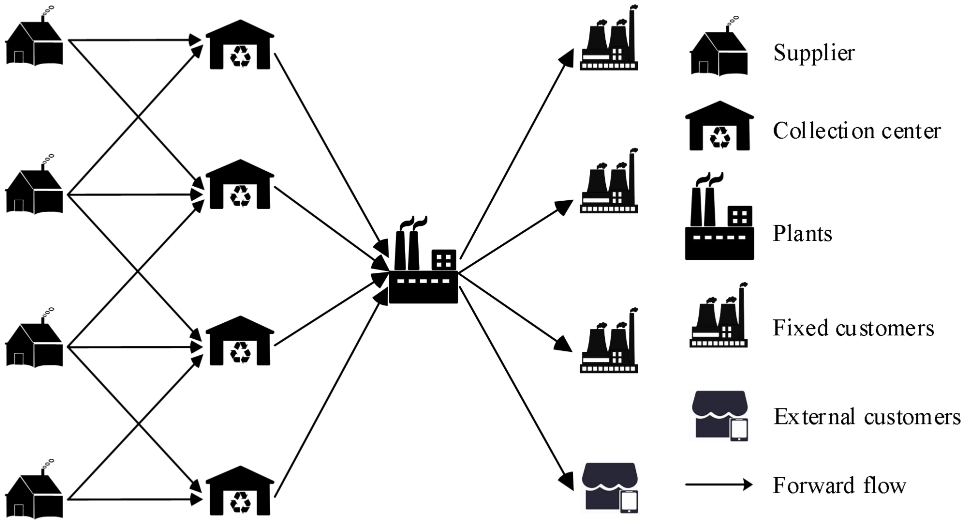

Fig. 1. Proposed reverse logistic network

The problem discussed in this paper is a multi-echelon multi-product multi-objective problem considering inventory strategy. The proposed model considering the following assumptions and limitations:

(1) The demand of the fixed customers is fixed.
(2) The supply of suppliers every month is fixed and known.
(3) The production of the plant is fixed in different levels.
(4) The collection centers are divided into several levels with fixed capacity.
(5) The quantity of price, production costs, fixed costs, transportation costs, storage costs, demands of fixed customers are known.
(6) The other costs are known.

Notation in the model formulation

Sets

H	Set of months, $h = 1,2,\ldots,12$
I	Set of locations of biomass suppliers, $i = 1,2,\ldots,I$
J	Set of potential locations of collection centers, $j = 1,2,\ldots,J$
K	Set of capacity level available for collection centers and the plant, $k = 1,2,\ldots,H$
M	Set of potential locations of customers, $m = 1,2,\ldots,M$
N	Set of biomass, $n = 1,2,\ldots,N$

Parameters

Fixed costs:

Fcc_{jc}	Fixed cost of opening collection center j with capacity level of k every month
Fcp_k	Fixed cost of opening the plant with capacity level of k every month

Variable costs:

Pur_n	Purchasing cost per ton of biomass n
Pre_n	Pretreatment cost per ton of biomass n
Pro	Production cost per ton
Sc_n	Storage cost of pretreated biomass n per ton per month
Pbf	Price of biofuel per ton at fixed customers
Pbe	Price of biofuel per ton at external customers

Transportation costs:

Tbm_n	Unit transportation rate for biomass n
Tpb_n	Unit transportation rate for pretreated biomass n
Tb	Unit transportation rate for biofuel

Transportation distances:

Dsc_{ij}	Distance from supplier i to collection center j
Dcp_j	Distance from collection center j to the plant
Dpc_m	Distance from the plant to customer m

Carbon emission coefficient：

Epb_n	Carbon emission coefficient of pretreating biomass n per ton
Esc_n	Carbon emission coefficient of storing per ton pretreated biomass n at collection center j per month
Epr	Carbon emission coefficient of producing biomass per ton
Esb_n	Carbon emission coefficient of shipping per ton biomass n per kilometer
Esp_n	Carbon emission coefficient of shipping per ton pretreated biomass n per kilometer
Ecs	Carbon emission coefficient of shipping per ton biofuel per kilometer

Capacity of facilities:

Cs_{in}^{h}	Capacity of supplier i for biomass n at month h
Cp_k	Capacity of the pant every month with capacity level k
Cc_{jk}	Capacity of collection center j with capacity level k

Others:

Rbm_n	Rate of pretreated biomass n to biomass n
Rbb_n	Rate of biofuel to pretreated biomass n
Dem_m	Demand of fixed customer m every month

Decision variables:

Ipb_{nj}^h	Initial inventory of pretreated biomass n at collection center j on month h
Qsc_{nij}^h	Quantity of biomass n shipped from supplier i to collection center j on month h
Qcp_{nj}	Quantity of pretreated biomass n shipped from collection center j to the plant every month
Qpf_m	Quantity of biofuel shipped from the plant to fixed customer m every month
Qpe	Quantity of biofuel shipped from the plant to external customer every month
$X_{jk} = \begin{cases} 1 \\ 0 \end{cases}$	If collection center j with capacity level k is opened, Otherwise;
$Y_k = \begin{cases} 1 \\ 0 \end{cases}$	If the plant with capacity level k is opened, Otherwise;

Model formulation

The proposed model consists of two objectives functions and eleven constraints.

Objective function

The proposed model has economic, environmental, and social objective functions as follows.

$$\begin{aligned} Max\ f_1 = {} & 12(\sum_m Pbf \cdot Qpf_m + Pbe \cdot Qpe) - \sum_n \sum_i \sum_j \sum_k (Pur_n + Pre_n) Qsc_{nij}^k - 12(\sum_j \sum_k Fcc_{jk} X_{jk} \\ & + \sum_k Fcp_k Y_k) - \sum_n \sum_j \sum_k Sc_n \cdot Ipb_{nj}^k - 12\sum_m Pro(Qpf_m + Qpe) - (\sum_n \sum_i \sum_j \sum_k Tbm_n Qsc_{nij}^k Dsc_{ij} \\ & + 12\sum_n \sum_j Tpb_n Qcp_{nj} Dcp_j + 12\sum_m Tb(Qpf_m + Qpe) Dpc_m) \end{aligned} \tag{1}$$

$$\begin{aligned} Min\ f_2 = {} & \sum_n \sum_i \sum_j \sum_h Epb_n Qsc_{nij}^h + \sum_n \sum_j \sum_h Esc_n Ipb_{nj}^h + 12\sum_m Epr(Qpf_m + Qpe) \\ & + \sum_n \sum_i \sum_j \sum_h Esb_n Qsc_{nij}^h Dsc_{ij} + 12\sum_n \sum_j Esp_n Qcp_{nj} Dcp_j + 12\sum_m Ecs(Qpf_m + Qpe) Dpc_m \end{aligned} \tag{2}$$

The objective function (1) is to maximize the total profit which is obtained by subtracting total cost from total income. The costs of supply chain include purchasing cost of biomass, production cost of products, storage cost of product at collection centers, pretreatment cost of biomass and transportation cost. The objective function (2) is to minimize the total carbon emissions during producing, storing, pretreatment, shipping of the biomass, pretreated biomass and biofuel.

Constraints

The proposed model consists of several constraints: flow constraints, capacity constraints, and others.

$$\sum Qsc_{nij}^h \le Cs_{in}^h, \forall n, i, h \tag{3}$$

$$Ipb_{nj}^h + Rbm_n \sum Qsc_{nij}^h - Qcp_{nj} = Ipb_{nj}^{h+1}, \forall n, j, h (h \le 11) \tag{4}$$

$$Ipb_{nj}^{12} + Rbm_n \sum Qsc_{nij}^{12} - Qcp_{nj} = Ipb_{nj}^1, \forall n, j \tag{5}$$

$$\sum \sum Qcp_{nj} Rbb_n = \sum Qpf_m + Qpe \tag{6}$$

$$Qpf_m = Dem_m, \forall m \le M - 1 \tag{7}$$

$$0 \le \sum Ipb_{nj}^h \le \sum Cc_{jk} X_{jk}, \forall j, h \tag{8}$$

$$\sum\sum Qcp_{nj} \le \sum Cp_k Y_k \tag{9}$$

$$\sum X_{jk} \le 1, \forall j \tag{10}$$

$$\sum Y_k = 1 \tag{11}$$

$$X_{jk}, Y_k \in \{0,1\}, \forall j,k \tag{12}$$

$$Ipb_{nj}^{h}, Qsc_{nij}^{h}, Qcp_{nj}, Qpf_m, Qpe \ge 0, \forall h,m,n,i,j \tag{13}$$

The constraint (3) means that the sum of quantity of biomass shipped to collection centers is no more than the capacity of the suppliers. The constraint (4) and (5) mean that for each collection center j, the inventory of latter month is equal to the inventory of former month plus the quantity of biomass pretreated on the former month and then minus the quantity of pretreated biomass shipped to the plant on the former month. The constraint (6) means that the quantity of biofuel produced is equal to the quantity shipped to the customers. The constraint (7) means that for each fixed customer, the quantity of biofuel it received is equal to its demand. The constraint (8) means that inventory of collection centers is no less than zero and no more than its capacity. The constraint (9) means that the quantity of biofuel produced is no more than the capacity of the plant. The constraint (10) means that each collection center can have one capacity level at most. The constraint (11) means that the plant has a fixed capacity level. The constraint (12) and (13) impose the binary and non-negativity restriction on the corresponding decision variables.

Solution method

The approach applied in this study to deal with multi-objective problem is two-stage fuzzy method. The procedure of two-stage fuzzy method can be described as follows:

Step 1: Determine the maximum bound and the minimum bound for each objective function:

$$\begin{aligned} f_1^+ &= \max_{x\in X} f_1 \\ f_2^+ &= \min_{x\in X} f_2 \\ f_1^- &= \min_{x\in X} f_1 \\ f_2^- &= \max_{x\in X} f_2 \end{aligned} \tag{14}$$

Step 2: Find the maximum satisfaction $\lambda^{(1)}$ of the target set and the feasible solution $x^{(1)}$ of the original problem:

$$\begin{aligned} \max \quad & \lambda \\ \text{s.t.} \quad & \lambda \le \frac{f_1 - f_1^-}{f_1^+ - f_1^-} \\ & \lambda \le \frac{f_2^- - f_2}{f_2^- - f_2^+} \\ & x \in X \end{aligned} \tag{15}$$

Step 3: Check the efficiency of $x^{(1)}$ or find new efficient solution $x^{(2)}$. If $x^{(2)}=x^{(1)}$, then, they are all the feasible solution of the original problem, otherwise, $x^{(2)}$ is an efficient solution of the original problem:

$$\begin{aligned} \max \quad & \bar{\lambda} = \frac{1}{2}(\lambda_1 + \lambda_2) \\ \text{s.t.} \quad & \lambda \le \lambda_1 \le \frac{f_1 - f_1^-}{f_1^+ - f_1^-} \end{aligned} \tag{16}$$

$$\lambda \le \lambda_2 \le \frac{f_2^- - f_2}{f_2^- - f_2^+}$$
$$x \in X$$

Step 1 and step 2 form the first stage, and step 3 is the second stage.

Computational results

In this section, a case study is used for evaluating the applicability of the developed model and the proposed solution method. The developed model was coded using MATLAB 2015b with YALMIP toolbox, and solved by the solver of CPLEX 12.5.

First, the Max and the Min bounds for the two objectives needed to be determined. The results are showed in Table 1. Then, the maximum satisfaction degree $\lambda^{(1)}$ of the objective set is calculated out and the feasible solution $x^{(1)}$ of the original problem is determined. $\{\lambda, f_1, f_2\} = \{0.893176, 80289291.9753, 1970840.377\}$. The results of step 2 are showed in Table 2. Check the efficiency of $x^{(1)}$. $\{\bar{\lambda}, \lambda_1, \lambda_2, f_1, f_2\} = \{0.893176, 0.893176, 0.893176, 80289291.9753, 1970840.377\}$ and $x^{(2)} = x^{(1)}$. The results of step 3 are showed in Table 3. It can be seen that $x^{(1)}$ is the finally result of the model.

Table 1 Results of the Step 1

f_1^+	f_2^+	f_1^-	f_2^-
84048984.2552	1601243.4987	48853688.7701	5061120.0989

Table 2 Results of Step 2

λ	f_1	f_2
0.893176	80289291.9753	1970840.377

Table 3 Result of Step 3

$\bar{\lambda}$	λ_1	λ_2	f_1	f_2
0.893176	0.893176	0.893176	80289291.9753	1970840.377

Conclusions and future research

In this article, a multi-objective optimization model considering inventory strategy for biofuel supply chain design is presented with two objectives: the maximization of the profit of the biofuel supply chain, and the minimization of the Carbon emissions. In order to solve the multi-objective model, we try to use the two-stage fuzzy method to transform the model to a single objective form.

In the solving period, the first is to determine the maximum bound and the minimum bound for each objective function; then find the maximum satisfaction $\lambda^{(1)}$ of the target set and the feasible solution $x^{(1)}$ of the original problem; finally, check the efficiency of $x^{(1)}$ or find new efficient solution $x^{(2)}$.In order show the applicability of the model in the real world, the suggested model is applied to straw recycling. By solving the case study, we have obtained the solution of the biofuel supply chain.

For further study, researchers can change the definition of objective functions, especially the social objective to include issues such as the maximization of the recovery of biomass recourses.

Moreover, the application of the proposed model and solution procedures in other biomass material can be an interesting research topic.

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