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Increasing Biofuel Proliferation via the Optimal Use of Government Incentives

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Keywords

Biofuel, transportation, sustainability, optimization

Disciplines

Agribusiness | Business Administration, Management, and Operations | Entrepreneurial and Small Business Operations | Management Information Systems | Operations and Supply Chain Management

Comments

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With the increasing public awareness on global warming, the demand for low greenhouse gas emission (GHG) transportation fuel, such as biofuel, is growing rapidly. In the U.S., like many other countries, the government is providing monetary incentives for biofuel displacement of fossil fuel. From the standpoint of biofuel proliferation, it is important that biofuel producers utilize these incentives in the most effective way, because better utilizations of incentives will lead to reduced costs for producers, which in turn will lower biofuel retail prices. Currently, however, biofuel producers are not taking full advantage of these incentives. This industry note introduces a new approach that allows U.S. biofuel producers to improve their practice of using an incentive program called the LCFS (California Low Carbon Fuel Standard). Our method, which is relatively simple, is based on a recent research project conducted with a biofuel manufacturing firm, which aimed to maximize the benefit gained from the LCFS incentive program. We show, by performing numerical experiments with realistic settings, that the method matches or outperforms the current practice, in terms of maximizing gains extracted from the incentive program, under all conditions.

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Introduction

Given the increasing public awareness on global warming, green and sustainable supply chain management has received much attention recently from many researchers and organizations alike. Transportation has a major impact on the greenness of supply chain activities in the form of energy consumption and carbon emissions (Tiwari and Chang 2015). In the U.S., transportation accounts for 29% of greenhouse gas emissions (U.S. Environmental Protection Agency 2019), and has a major impact on the greenness of supply chain activities. As such, the demand for the low greenhouse gas emission (GHG) transportation fuel is growing rapidly in the supply chain arena.

One type of low-emission transportation fuel is biofuel, the fuel made from a renewable, biological source. Biofuel GHG emissions, when added from source material production through biofuel production and transportation (cradle-to-grave life cycle emissions), can be 50% or less than the emissions from fossil fuels (Larson 2006; Varanda et al. 2011). Furthermore, biofuel is considered near-term abundant, because it can be easily produced from raw agricultural materials, meaning that the reservoir of fuel will never end (we can keep producing it). Given these features, legislation at both the federal and state level in the U.S. is providing incentives and/or enforcing requirements to encourage biofuel displacement of fossil fuel in transportation. Partly because of these legislative efforts, the biofuel production is increasing. It is projected that the U.S. biofuel production reaches 102 million Mtoe (millions of tons of oil equivalent) by 2030, up 183% from 36 Mtoe in 2018 (GreenFacts 2019).

One biofuel incentive program used in the U.S. is California Low Carbon Fuel Standard (LCFS) (note that LCFS is actually a “regulatory requirement” rather than an incentive, but we call it as “incentive” in this paper, following the tradition used by practitioners). In the states that enforce LCFS, regulated parties (typically biofuel buyers; e.g., Exxon, Texaco, etc.) are required to buy certain amounts of carbon credits within the specified time period. Typically, credits are purchased from biofuel producers together with biofuel products (each biofuel product has its own credit value, so that the purchase of a biofuel product generates credits). However, the parties can also buy only the credits in the carbon market, where surplus credits are sold by biofuel producers. Note that, since not all the buyers need carbon credits (e.g., firms that already purchased sufficient credits), some buyers only buy physical gallons without acquiring carbon credits (to save cost). In such cases, biofuel producers can separate carbon credits from biofuel products (sell only physical gallons to buyers) and trade the retained credits in the market. Biofuel buyers with sufficient credits may also sell their surplus credits in the market. This LCFS credit system allows biofuel producers to generate additional revenue by selling carbon credits (with biofuel or in the market).

It is important that, from the standpoint of biofuel proliferation, biofuel producers utilize the government incentive programs like the LCSF in the most effective way. This is because, unless the producers take full advantage of the programs, the retail prices of biofuel will be high (as better utilizations of the incentives should lead to reduced costs for producers), which can discourage the proliferation of biofuel in our society. This means that, with the presence of incentive programs such as the LCFS, biofuel producers must shift their objective from minimum cost delivery to maximal profit supply chain operations across geographically disbursed points (sourcing, manufacturing, and customer locations), resulting in the optimal combination of cost and incentive. Currently, however, the biofuel producers are not, as we shall see later, taking full advantage of the LCFS program, resulting in inefficient supply chain operations.

This article introduces a method that allows U.S. biofuel producers to take full advantage of the LCFS program by optimizing their supply chain operations. Our approach is based on the recent research project conducted with a biofuel manufacturing company (denoted Company X in the rest of this article to protect their identity), which aimed to maximize the company's revenue from LCFS credits, while also minimizing their costs of biofuel production and supply chain operations. Our method is relatively simple, and can be implemented by using a variant of a standard network optimization (LP) model. For biofuel producers with relatively simple supply chains, our approach can be implemented via the use of a spreadsheet optimizer. We demonstrate the method by performing numerical experiments with realistic settings, and show that the method either matches or outperforms the current practice, in terms of profit maximization, in all cases.

Literature Review

When we started the research project for Company X, we reviewed the biofuel supply chain literature to find out if there is any existing approach (or model) that can be used for this project. Table 1 lists the articles we found in the literature. The table summarizes articles by the following five aspects: (1) focus and goal, (2) number of supply chain echelons considered, (3) whether or not government incentives are considered, (4) methods used, and (5) how variables for inbound and outbound flows are specified (separate or combined). Major findings from the table follow.

(Insert Table 1 about here)

First, biofuel supply chain research started in the 2000's and became popular in the last decade. Second, the literature covers a wide range of modeling and solution approaches associated with supply-chain decision problems, most of which considered all echelons of the supply chain. Third, there is no article that considered government incentives, except You and Wang (2012) (which did not consider LCFS), nor are there articles that used decision variables that can trace the flow of materials all the way from the biomass source to the end customer (which, as we shall see later, is required to optimize LCFS credits). This condition suggests that, while the biofuel supply chain literature is becoming rich, no approach exists in the literature, as of today, that can help Company X take full advantage of the LCFS incentive program.

LCSF credits

Biofuel producers can gain LCFS credit revenues from two sources; i.e., by selling credits together with biofuel products or by selling the retained credits in the market (as discussed earlier). In this study we focus on maximizing the revenue gained from the former source. This decision was mainly driven by the expert inputs obtained from Company X, which suggested that the revenue gained from the former source is substantially larger than that from the latter source. Our discussions that follow, therefore, will focus on describing the nature and current practice of the former source (i.e., LCFS credits that are sold directly to buyers together with biofuel products).

LCFS is a state-level program that determines the renewable fuel value for each product of transportation fuel based on its ability to reduce the carbon intensity (denoted CI, which represents the amount of carbon emitted per unit of energy consumption). The program assigns a target CI for the state. Fuel products with carbon intensity that do not meet (i.e., are higher than) the target CI generates carbon deficits, whereas those that meet or exceed (are lower than) the target CI generates carbon credits. Regulated parties (typically biofuel buyers; e.g., Exxon, Texaco, etc.) with carbon deficits must purchase credits that may be obtained from biofuel producers when purchasing credit-generating fuel or in the market after the credit has been separated from fuel (as discussed earlier). The LCFS program mandates that the target CI decreases over time. This requires buyers to purchase greater volumes of renewable fuel over time, and also incentivizes biofuel producers to develop fuel technologies with more aggressive carbon reduction capacities.

LCFS credit is determined uniquely for each biofuel product based on which feedstock, which processing plant, and which transportation mode are used to produce the biofuel (i.e., LCFS value is unique to each feedstock-plant combination, given the transportation mode). Essentially, LCFS credit measures the extent to which the feedstock and the plant that are used to produce the biofuel can reduce the CI of the final product (that is, the lower the CI, the higher the LCFS credit the product can earn). The number of states enacting low carbon fuel regulations and markets are increasing, but as of now it is far less than 100%, which means that not all the biofuel customers buy LCFS credits. Since the LCFS revenue is realized by biofuel producers only if they sell biofuel to the customers who buy LCFS credits (credit-generating customers, e.g., California customers), it is best for biofuel producers to sell low-CI (high LCFS) products to such customers. In theory, this can be accomplished by shipping products made from the feedstock-plant combinations that can earn the highest LCFS values to such customers, and other products to non-credit customers.

In practice, however, it is difficult for producers to ship products in this way, because at each manufacturing plant the biofuel products produced from different feedstock are mixed in the "finished good" storage bins, so that it is difficult for producers to know the exact LCFS value of the product shipped to each individual customer. To see this point, we refer the readers to Figure 1, which shows a simple biofuel supply chain consisting of three echelons; namely, raw material (feedstock) vendors, processing plants, and customers (buyers). Notice that, in Figure 1, the biofuel shipped from plant II to customer 1 is a mix of biofuel products made from feedstock A, B, and C, so that it is difficult for the producer to determine precisely from which feedstock the biofuel shipped to customer 1 is made, and thus how much LCFS credit is to be transferred to customer 1.

(Insert Figure 1 about here)

Given this issue, the government allows producers to "mass balance" the LCFS credits for physical gallons delivered to customers. This means that credits can be assigned conveniently (flexibly) to delivered gallons, such that the product with the highest LCFS credit can be assigned to credit-generating customers and that with the lowest LCFS credit can be assigned to no-credit customers, as long as: (1) gallons assigned (assumed to be shipped) to a given customer k equals the amount actually delivered to k, and (2) total outbound shipment assumed for a given plant j (sum of gallons assumed to be shipped from j to all customers) does not exceed the amount produced at j. For instance if, at plant II, the biofuel produced from feedstock A gives the highest LCFS credit (higher than those produced from B or C), and if customer 1 is the only customer that buys LCFS credit, the firm can conveniently assume that the biofuel sold to customer 1 from plant II is all made from feedstock A (provided that the production at plant II from feedstock A is not less than the amount shipped to customer 1). This allows producers to maximize LCFS revenues.

Current business practice (including that of Company X) attempts to take advantage of the "mass balancing" rule by using a two-step procedure, where they first solve a standard network optimization model to obtain the optimal (minimal cost) solution that determines the flow of feedstock and finished product (biofuel) in their network, and then use a simple procedure to determine the LCFS credit value for each customer that seemingly maximizes the overall LCFS revenue for the company. It can be shown, however, that this practice (two-step procedure) does not necessarily maximize profits for companies, and that there is a better (more effective) way of determining both the step 1 solution (controlling material flow in a network) and the step 2 solution (finalizing LCFS credit for each customer) jointly. Details are discussed in the next two sections.

Current Practice

We start by describing the current practice. The first step involves solving the network optimization problem (model) in a standard way. Due to space limitations, this model is not presented here, but the sketch of this model is discussed below (details are available upon request).

The objective function minimizes the cost of a supply-chain network, which includes the feedstock purchase cost, inbound freight cost (vendors to plants), plant processing cost, and outbound freight cost (plants to customers). The sets of constraints are imposed to ensure that: (1) the amount of feedstock shipped from each vendor does not exceed the available amount, (2) the inflow and outflow of materials (feedstock and processed biofuel) at each plant always balance, (3) production at each plant does not exceed its capacity, and (4) the demand of each customer is fully satisfied (because the demand for biofuel producers represents the "committed" amount; i.e., producers have already signed a contract with each customer to ship a specified amount).

Two sets of non-negative decision variables are used in this model; namely x_{ij}, which indicates the amount (gal.) of feedstock type $i \in N$ shipped to plant $j \in M$, and x_{jk}, which indicates the amount (gal.) of biofuel shipped from plant $j \in M$ to customer $k \in \Omega$ (where N, M, and Ω are sets of all feedstock vendors, plans, and customers, respectively). This model can be formulated as a linear program, and thus can be solved to optimality, by using standard simplex solvers. This allows biofuel producers to obtain an optimal (minimal-cost) solution that determines the flow of materials in their supply chain networks. Hereafter this network model is referred to as Model 1.

The second step involves determining the LCFS credit for each customer so as to maximize the company revenue, given Model 1 solution (we consider only the LCFS revenue and ignore the revenue from biofuel sales, as the latter revenue is fixed given that biofuel producers must, as discussed earlier, always satisfy all the customer demands in full). Let L_{ij} be the LCFS value per gallon obtainable from feed stock $i \in N$ and plant $j \in M$ combination, σ_k be the 0/1 constant indicating whether customer $k \in \Omega$ buys LCFS credit or not (1 = credit, 0 = no credit; note that σ_k can be a fractional value between 0 and 1 if k gives a partial credit), and z_{ijk} be the "convenient" amount of biofuel (gal.) produced from feedstock i at plant j that are assumed to be shipped to customer k (amount to be reported for "mass balancing" purpose). The goal is to determine z_{ijk} for all i, j, k, such that the amounts of biofuel having the highest L_{ij} values, which are assumed to be shipped to credit-generating customers ($\sigma_k = 1$), are maximized, subject to that (for all i, j, k) z_{ijk} does not exceed the actual biofuel produced from feedstock i at plant j (based on Model 1 solution), or the actual biofuel shipped from plant j to customer k (based on Model 1 solution). The solution to this second-step problem can be obtained by using a simple algorithm shown in Figure 2.

(Insert Figure 2 about here)

It is clear that the above two-step procedure, which reflects the practice, gives only a sub-optimal solution, as it solves the two problems (steps 1 and 2) independently (sequentially). To obtain an optimal solution that maximizes profit (revenue less operating cost), we must incorporate the LCFS credits into the network model, and solve steps 1 and 2 jointly. This, however, may not be accomplished when using the standard network models, because in standard network models the decision variables determine only the flow of materials from one echelon to the next (e.g., from vendors to plants, or from plants to customers), meaning that they cannot be used to determine z_{ijk} values. In the next section, we propose a network modeling approach that allows biofuel producers to improve their profits considerably by solving steps 1 and 2 of the current practice jointly.

Proposed Approach

Let us introduce a new decision variable x_{ijk}, which indicates the non-negative amount (gal.) of biofuel produced from feedstock i at plant j that is (assumed to be) shipped to customer k. It is essentially the same as z_{ijk} variable used in the previous section, except that it not only reflects the "conveniently defined" amount of biofuel moving from i via j to k (which was the case for z_{ijk}), but also determines the "actual" material flows in the network. That is, while the x_{ijk} value can reflect the "hypothetical" or "conveniently defined" amount of biofuel moving from i via j to k (for reporting purposes), the echelon-to-echelon movement of materials derived from its value, namely $\sum_k x_{ijk}$ and $\sum_i x_{ijk}$, must reflect the actual flow of materials from vendor i to plant j and that from plant j to customer k respectively (for all i, j, k). This variable specification allows us to determine both the "conveniently defined" and "actual" flows of materials simultaneously.

With this new variable specification, we can write a new network optimization model that solves steps 1 and 2 of the current practice jointly. This new model is denoted as Model 2 from now on. Again, Model 2 is not presented in this article for space limitations, but the sketch of the model is discussed below (details of Model 2 are available to the interested readers upon request).

The objective function maximizes profit, which is given by the LCFS revenue less the feedstock cost, inbound freight cost, plant processing cost, and outbound freight cost. Constraints for Model 2 ensure that: (1) each vendor cannot ship more feedstock than the available amount, (2) each plant cannot make more biofuel than its processing capacity, and (3) each customer's demand must be fully satisfied. Note that, unlike Model 1, there are no flow-balance constraints imposed on plants, as they are naturally satisfied because of the way the decision variable (x_{ijk}) is defined. Also note that the constraints (1)-(3) above control only the "actual" flows of materials, not the "hypothetical" flow of materials for mass-balancing purposes (e.g., how many gallons of biofuel produced at plant j from feedstock i is assumed to be shipped to customer k), meaning that the latter flow is determined in the most convenient way for the producer to maximize LCFS credits. Model 2, like Model 1, can be solved to optimality by using standard simplex solvers.

There are two important advantages of using Model 2. First, unlike the current practice (two-step procedure), Model 2 always gives the optimal solution by jointly considering steps 1 and 2 of the current practice (i.e., Model 2 makes the best trade-off between minimizing cost and maximizing LCFS revenue). Second, Model 2 is simpler than the current practice. Note that, by using Model 2, biofuel producers no longer have to perform two separate procedures to calculate LCFS credits, but instead solve only one model. Furthermore, the formulation of Model 2 is, in a sense, simpler than that of Model 1, because the set of constraints required in Model 1 (plant flow constraints) is not needed in Model 2 (the readers familiar with network models may notice that, given this condition, Model 2 is akin to the "transportation model", which can be solved quickly).

It is worth noting that Model 2 can be used to perform the two-step procedure discussed in the previous section (current practice), but in a more effective way. To do this, we can first solve Model 2 by ignoring the LCFS revenue (i.e., minimize cost; step 1), and then solve Model 2 again (step 2) but this time by (1) ignoring costs (i.e., maximize LCFS revenue) and (2) forcing the cost

(Model 2 objective function less LCFS revenue) to be equal to that of step 1 solution (minimal-cost solution). This method (denoted as Lexicographic procedure) produces better solutions than the current practice. It is known that the optimal solution of a network model is often not unique. This means that there may be multiple Model 1 solutions with the same cost, each of which does not necessarily give identical LCFS credits after applying the second-step procedure (algorithm) discussed earlier. In the traditional two-step procedure, therefore, the solution which is passed on to the second step (a minimal-cost solution) may not be the one corresponding to the solution giving the maximal LCFS credits. In contrast, the above Lexicographic procedure will always choose, in its second step, the minimal-cost solution that generates the maximal LCFS revenue.

In short, the proposed network approach discussed in this section should, in theory, provide better results to biofuel producers. Most biofuel producers may be interested in using Model 2 “as is” to maximize their profits, but some producers may be interested in using the Lexicographic procedure to minimize their cost while also improving (but not maximizing) LCFS revenues. Note that since the Lexicographic procedure can possibly give lower costs than Model 2 (Model 2 needs not generate minimal-cost solutions because its goal is to maximize profit), the former procedure may be valuable to biofuel producers that are having cash-flow problems, as they may be interested more in minimizing cost (cash outflows) than in maximizing revenue (cash inflows). In the next section, we address the question “When and by how much can the profit be improved by using the proposed approach?”, at least partially, by conducting a simple experiment with realistic data.

Case Study and Experiment

The actual optimization model we developed for Company X is far more complex than the models discussed in this article. This is because the actual model incorporates: (1) a notably larger number of nodes (vendors, plants, customers), (2) decisions regarding future revenues (choosing most attractive sets of customers to commit future sales), (3) plant processing decisions (imposing production lower bound on each plant to prevent small-scale manufacturing, which requires the use of integer variables), (4) other cost elements affecting material-flow decisions (e.g., inventory carrying cost), (5) transshipments among plants (e.g., moving inventory from small plants to larger plants), and (6) beginning inventory effects (leftover products from the previous planning period).

The non-disclosure agreement we made with Company X prevents us from illustrating the full specification of the actual model, but this section conducts a small-scale experiment to demonstrate how our approach can improve the profits of biofuel producers. The experiment is conducted by using an abridged supply-chain network of Company X (a small replica that mimics their network) and the sample data obtained from them (the data shown later are distorted to protect their identity). Although we use small networks to conduct an experiment, they are sufficient to demonstrate the approach, as the basic concept works equally well in small and large networks.

(Insert Tables 2 to 5 about here)

The network used in our testing consists of 4 feedstock vendors, 3 manufacturing plants, and 3 biofuel buyers. The testing was executed in Microsoft Excel, along with Frontline Systems Analytic Solver Platform (this spreadsheet is available to the interested readers upon request). The parameters (data) used in our experiment are shown in Tables 2 to 4. Our experiment is designed to contrast the performance of the existing method (heuristic solution given by the two-step procedure) with the two methods introduced in this article (Lexicographic procedure and the proposed method, which is given by the optimal Model 2 solution). Our experiment considers 12 different scenarios, the details of which are provided in Table 5. The use of these 12 scenarios in our testing allows us to empirically examine the performance of the two methods presented in this article, vis-a-vis that of the existing heuristic method, under different settings. Experimental results are reported in Table 6. Note that in all the instances (scenarios), it is assumed that the total revenue derived from biofuel sales is fixed at $31,120,000, because we assume that (as discussed earlier) a biofuel producer must always satisfy the demand of all the customers in full (completely).

(Insert Table 6 about here)

Results show that, as expected, the proposed method always provides the highest profit in all the scenarios (1 through 12). Note that the proposed method outperforms both the heuristic and Lexicographic methods in every instance, and that, with the use the proposed method, the profit can increase, on average, by 29% over the heuristic method and by 17% over the Lexicographic method. Results also show that the Lexicographic procedure either matches or outperforms the heuristic method in every instance. Specifically, the Lexicographic procedure achieves higher profits than the heuristic method in 6 out of 12 instances and achieves the same profit in the remaining 6 instances. All of these results provide strong evidence that the methods presented in this article can offer considerable benefits, in the form of improved profits, to biofuel producers. It should be noted, however, that the performance gap between the methods seems to vary considerably across scenarios. This implies that there may be certain conditions under which the methods presented in this paper may (or may not) work well. Given this finding, we investigate the impact of experimental factors (σ_k values, plant capacity, LCFS multiplier) on performance gaps between the methods (percentage difference in profit) by creating a table (Table 7) which contrasts the average profit of the three methods under different values of experimental factors.

(Insert Table 7 about here)

Table 7 suggests the following. First, the performance gap between the proposed and the heuristic methods generally increase when the number of credit-generating customers and/or the plant capacity increase, but not when the LCFS credit multiplier increases. This means that, with the diffusion of biofuel (which results in larger biofuel production capacities and larger number of credit-generating customers), the proposed method may become even more valuable to biofuel producers as a profit-improving tool. This also means that, with the increase in LCFS credit value (which can be triggered, for example, by the advancement of biofuel production technologies), the heuristic method may become quite effective, such that the amount by which the proposed method outperforms the heuristic method, while always positive, may diminish. Second, the gap between the Lexicographic and the heuristic methods becomes large when the plant capacity increases, but not necessarily when the number of credit-generating customers, or the LCFS credit multiplier, increases. This means that, although the Lexicographic procedure always matches or outperforms the heuristic method, the condition under which the former works most effectively may be unclear.

Our experimental results provide two normative implications to biofuel producers. First, the two-step procedure currently used in practice gives only sub-optimal solutions. Our results showed that profit-maximizing solutions do not necessarily minimize costs. This means that the current practice, which first minimizes costs and then maximizes revenue, need not optimize profits. Second, our approach may improve the profits of biofuel producers considerably. Biofuel producers' profit margins are typically thin, which means that even a slight increase in revenue (improved LCFS credits, which can be realized by using the proposed approach), can notably enhance their profits. Our results showed that the approach may improve their profits by 29%.

Conclusion

The proposed supply-chain optimization approach may provide considerable benefits to biofuel producers. Given that the number of states adopting the LCFS program is increasing (California and Oregon have already adopted, and Washington, New York, and Colorado are considering; see, e.g., Actnews 2109), the benefits the approach can give to producers may become even larger in the future. We hope that the approach presented in this article becomes a useful decision tool, which can be used conveniently by biofuel producers of all sizes (small or large), to accelerate the diffusion of biofuel, and thus the creation of greener environments, in the future. Our approach may also be applied to other industries where mass-balancing is allowed when computing credits gained from the use of renewable energies. Such industries may include cotton, superabsorbent, and plastics industries. Future works may consider applying the proposed framework to these industries.

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Figure 1: Sample network diagram

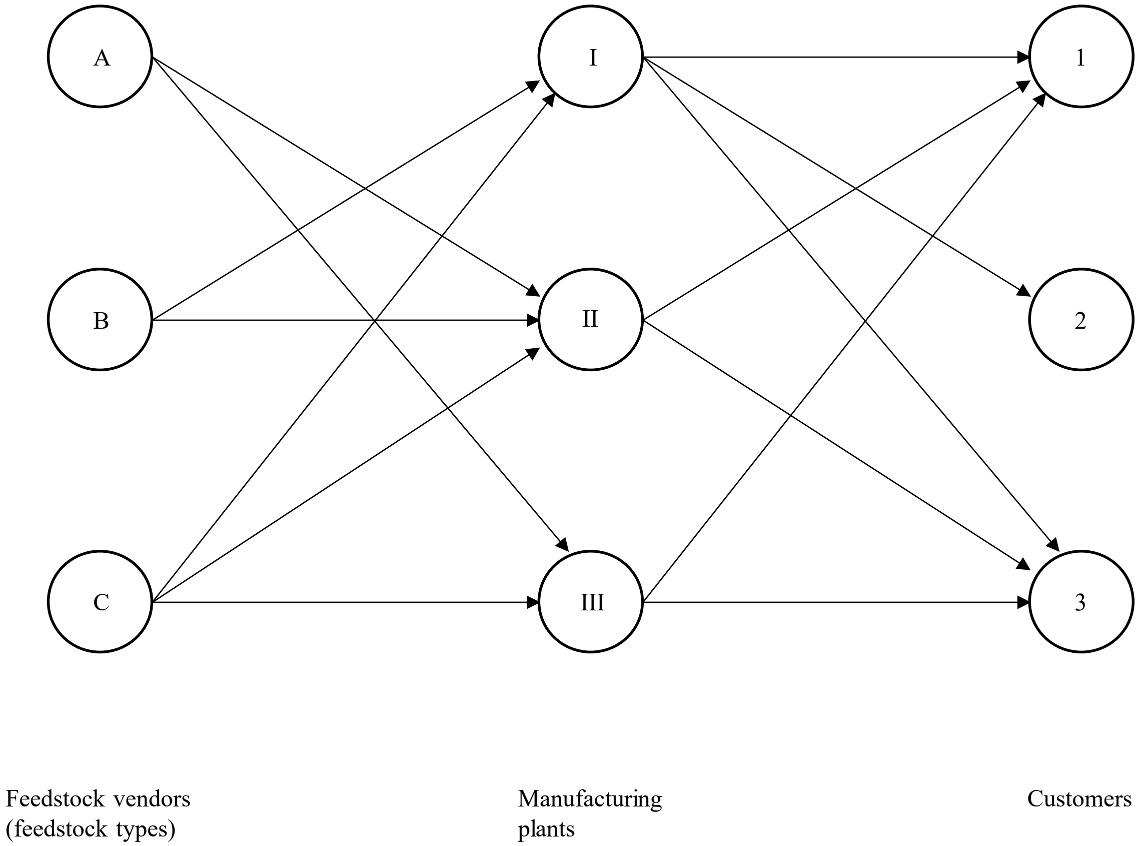

Figure 2: Second-step algorithm

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Step 1: Compute $\theta_{ijk} = L_{ij}\sigma_k \ \forall \ i, j, k$.
Step 2: Sort $\theta_{ijk}$ in descending order.
Step 3: Let $q = 1$
Step 4: Let $\{i^*, j^*, k^*\}$ be the set (combination) of vendor, plant, and customer that yields the $q^{th}$ highest
        $\theta_{ijk}$ value ($q^{th}$ member of the sorted vector created in Step 2).
Step 5: Set $z_{i^*j^*k^*} = min\{\hat{x}_{i^*j^*}, \hat{x}_{j^*k^*}\}$.
Step 6: Set $\hat{x}_{i^*j^*} \leftarrow max\{0, \hat{x}_{i^*j^*} - z_{i^*j^*k^*}\}$,   $\hat{x}_{j^*k^*} \leftarrow max\{0, \hat{x}_{j^*k^*} - z_{i^*j^*k^*}\}$.
Step 7: Increment $q$ by 1.
Step 8: If $q > |N| \times |M| \times |\Omega|$, terminate algorithm.  Otherwise return to Step 4.
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Table 1. Biofuel supply-chain literature

Authors	Year	Focus and Goal	Echelons	Gov't Incentive	Method	Inbound outbounc
Awudu, I., and J. Zhang	2013	Future research based on incorporating uncertainties and sustainability concepts within the biofuel supply chain	All 3	No	Overview and Literature Review	–
An, H., E. W. Wilhelm, and S. W. Searcy	2011	Provide a review of previous research based on a decision time frame and the level in the supply chain (i.e., upstream, midstream, and downstream).	All 3	Yes	Overview and Literature Review	–
Ba, H. B., C. Prins, and C. Prodhon	2016	Underline the contributions and shortcomings of current research and suggest possible directions	All 3	No	Overview and Literature Review	–
Atashbar, N. Z., L. Nacima, and C. Prins	2017	Give a comprehensive overview of the research in the field with a focus on optimisation modelling issues and solution approaches.	All 3	No	Overview and Literature Review	–
Huang, Y., C-W. Chen, and F. Yueyue	2010	Propose a model to minimize the cost of the entire biofuel supply chain over the entire planning horizon, simultaneously satisfying demand, resource, and technology constraints.	All 3	No	Mixed integer programming	Separate
An, H., E. W. Wilhelm, and S. W. Searcy	2011	Study the most profitable biofuel supply chain design under different scenarios based on a multi-commodity flow model which includes different types of feedstock and biofuel.	All 3	No	Mixed integer programming	Separate
You, F., and B. Wang	2012	Present a multi-objective model for the trade-off between economic and environmental impacts across all echelons of the biofuel supply chain.	All 3	Yes	Multi-objective mixed integer programming	Separate
Awudu, I., and J. Zhang	2013	Propose a stochastic production planning model for a biofuel supply chain under demand and price uncertainties.	All 3	No	Stochastic linear programming and Sensitivity Analysis	Separate
Azadeh, A., H. V. Arani, and H. Dashti	2014	Predict how to maximize expected profit and how profit changes due to existing uncertainties.	All 3	No	Stochastic linear programming and Sensitivity Analysis	Separate
Jinkyung, K., M. J. Reallf, J. H. Lee	2011	Propose a stochastic optimization model for the optimal design problem of biomass supply chain networks under uncertainty.	All 3	No	Two Stage Mixed Integer Stochastic Programming	Separate
Li, Q., and G. Hu	2014	Propose a stochastic optimization model to maximize biofuel producers' annual profit considering uncertainties in the supply chain.	All 3	No	Two Stage Mixed Integer Stochastic Programming	Separate
Huang, Y., F. Yueyue, and C-W. Chen	2014	Offer an integrated approach to identify strategies to mitigate the impact of uncertainty and seasonality in feedstock harvesting.	All 3	No	Two Stage Mixed Integer Stochastic Programming	Separate
Ekşioğlu, S. D., A. Acharya, L. E. Leightley and Arora, S.	2019	Propose an optimization model for upstream supply chains to determine the number, locations, and capacities of the biofuel production facilities based on biomass availabilities.	Vendors and Production Facilities	No	Mixed integer programming	–
Sun, F., M. M. Aguayo, R. Ramachandran, and S. C. Sarin	2108	Present a review of the modeling approaches for the biomass supply chains and a decomposition-based procedure to solve the facility location and vehicle routing problems.	Vendors and Production Facilities	No	Mixed integer programming and decomposition	–
Sokhansanja, S., A. Kumar, A. Turhollow	2006	Simulate the collection, storage, and transport operations for supplying agricultural biomass to a biorefinery.	Vendors and Production Facilities	No	Simulation	–

Table 2. Feedstock parameters

Feedstock (Vendor)	Price ($/pound)	Availability (pounds)	Yield[1] (gal.)	Freight cost to ($/pound)		
				Plant I	Plant II	Plant III
A	0.25	10,000,000	8.00	0.035	0.025	0.027
B	0.20	30,000,000	9.20	0.006	10.00	0.010
C	0.29	40,000,000	7.50	0.020	0.032	0.010
D	0.29	30,000,000	8.50	0.017	0.008	10.00

[1] Indicates the inverse of how much biofuel can be produced from one pound of feedstock.

Table 3. Plant parameters

	Process cost ($/gal.)	LCFS credit obtainable from feedstock[1]				Freight cost to ($/pound)		
		A	B	C	D	Cust. 1	Cust. 2	Cust. 3
Plant I	0.15	1.66	1.54	1.06	1.30	0.170	0.170	0.420
Plant II	0.10	0.00	0.00	1.10	0.00	0.040	0.040	0.530
Plant III	0.16	1.61	1.49	1.01	0.00	0.030	0.030	0.460

[1] These values represent credit values in dollars per gallon of produced biofuel.

Table 4. Customer parameters

	Biofuel demand (gal.)	Biofuel price charged ($/gal.)
Customer 1	4,000,000	1.92
Customer 2	3,000,000	2.68
Customer 3	5,000,000	3.08

Table 5. Scenarios tested

Scenarios	σ_k values of customers 1, 2, 3	Capacities of plants I, II, III (gal. in millions)	LCFS credits values[1]
1	(1, 1, 1)	(5, 6.5, 4)	1
2	(0, 1, 1)	(5, 6.5, 4)	1
3	(1, 0.85, 1)	(5, 6.5, 4)	1
4	(0, 0, 1)	(5, 6.5, 4)	1
5	(1, 1, 1)	(5, 6.5, 4)	1.2
6	(0, 1, 1)	(5, 6.5, 4)	1.2
7	(1, 0.85, 1)	(5, 6.5, 4)	1.2
8	(0, 0, 1)	(5, 6.5, 4)	1.2
9	(1, 1, 1)	(6, 6.5, 0)	1.2
10	(0, 1, 1)	(6, 6.5, 0)	1.2
11	(1, 0.85, 1)	(6, 6.5, 0)	1.2
12	(0, 0, 1)	(6, 6.5, 0)	1.2

[1] Multiplier that increases the LCFS credit values (1.2 means 20% increase from those shown in Table 3).

Table 6. Results

Scenario	Method	LCFS rev.	Total rev. (incl. sales)	Inbound freight cost	Feedstock cost	Plant cost	Outbound freight cost	Total Cost	Total Profit
1	Heuristic	10,480,758	41,600,758	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	11,072,624
	Lexicographic	10,480,758	41,600,758	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	11,072,624
	Proposed	15,486,539	46,606,539	1,678,388	25,414,040	1,690,000	2,340,000	31,122,428	15,484,111
2	Heuristic	6,837,674	37,957,674	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	7,429,540
	Lexicographic	9,878,474	40,998,474	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	10,470,340
	Proposed	11,157,472	42,277,472	1,489,429	25,414,040	1,690,000	2,340,000	30,933,469	11,344,003
3	Heuristic	6,837,674	37,957,674	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	7,429,540
	Lexicographic	9,422,354	40,542,354	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	10,014,220
	Proposed	10,597,215	41,717,215	1,489,429	25,414,040	1,690,000	2,340,000	30,933,469	10,783,745
4	Heuristic	6,837,674	37,957,674	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	7,429,540
	Lexicographic	6,837,674	37,957,674	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	7,429,540
	Proposed	7,722,005	38,842,005	1,341,513	25,414,040	1,690,000	2,340,000	30,785,553	8,056,453
5	Heuristic	12,576,910	43,696,910	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	13,168,776
	Lexicographic	12,576,910	43,696,910	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	13,168,776
	Proposed	18,583,847	49,703,847	1,678,388	25,414,040	1,690,000	2,340,000	31,122,428	18,581,419
6	Heuristic	8,205,209	39,325,209	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	8,797,075
	Lexicographic	11,854,169	42,974,169	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	12,446,035
	Proposed	13,463,767	44,583,767	1,563,388	25,414,040	1,690,000	2,340,000	31,007,428	13,576,339
7	Heuristic	8,205,209	39,325,209	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	8,797,075
	Lexicographic	11,306,825	42,426,825	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	11,898,691
	Proposed	12,716,658	43,836,658	1,489,429	25,414,040	1,690,000	2,340,000	30,933,469	12,903,188
8	Heuristic	8,205,209	39,325,209	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	8,797,075
	Lexicographic	8,205,209	39,325,209	1,084,094	25,414,040	1,669,710	2,360,290	30,528,134	8,797,075
	Proposed	9,266,407	40,386,407	1,341,513	25,414,040	1,690,000	2,340,000	30,785,553	9,600,854
9	Heuristic	12,959,997	44,079,997	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	13,083,384
	Lexicographic	12,959,997	44,079,997	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	13,083,384
	Proposed	17,887,287	49,007,287	2,078,013	25,414,040	1,500,000	2,510,000	31,502,053	17,505,234
10	Heuristic	12,173,082	43,293,082	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	12,296,469
	Lexicographic	12,200,082	43,320,082	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	12,323,469
	Proposed	13,356,127	44,476,127	2,039,763	25,414,040	1,475,000	2,445,000	31,373,803	13,102,324
11	Heuristic	11,581,188	42,701,188	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	11,704,575
	Lexicographic	11,604,138	42,724,138	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	11,727,525
	Proposed	12,742,669	43,862,669	2,039,763	25,414,040	1,475,000	2,445,000	31,373,803	12,488,866
12	Heuristic	8,227,122	39,347,122	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	8,350,509
	Lexicographic	8,227,122	39,347,122	1,662,572	25,414,040	1,475,000	2,445,000	30,996,612	8,350,509
	Proposed	9,266,407	40,386,407	1,956,513	25,414,040	1,475,000	2,445,000	31,290,553	9,095,854

Table 7. Average Comparisons

	Average profit by method			Improvement (%) attained		
Experimental factor	H	L	P	L vs. H	P vs. H	P vs. L
Num. of credit customers						
1	8,192,375	8,192,375	8,917,720	0.00	8.85	8.85
2	9,507,695	11,746,615	12,674,222	23.55	33.30	7.90
2.85	9,310,397	11,213,479	12,058,600	20.44	29.52	7.54
3	12,441,595	12,441,595	17,190,255	0.00	38.17	38.17
Combined plant capacity						
12.5	11,358,735	11,371,222	13,048,069	0.11	14.87	14.75
15.5	9,115,155	10,662,162	12,541,264	16.97	37.59	17.62
LCFS credit multiplier						
1	8,340,311	9,746,681	11,417,078	16.86	36.89	17.14
1.2	10,624,367	11,474,433	13,356,760	8.00	25.72	16.40

Note: H = heuristic, L = Lexicographic, P = proposed