Optimization of Biodiesel Supply Chain Produced from Waste Cooking Oil: A Case Study in China

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Abstract. The Chinese program for biodiesel use highlights the production of biodiesel from waste cooking oil (WCO). This paper addresses the design of a WCO-biodiesel supply chain and develops an advanced modeling framework to make decisions on location, production, inventory, and distribution in different settings. This paper proposes a four-stage model to optimize the biodiesel supply chain from both economic and environmental objectives. The first one is to minimize the collection facility and biorefinery construction costs associated with storage and transportation to the crushing plant. The second is to minimize GHG emissions within the whole process of WCO-biodiesel. Then the analysis is applied to a case study in Jiangsu of China where has realized application in WCO-biodiesel and have a great demand for biodiesel. The case is modeled using a spatially explicit integrated supply chain model. The resource is spatially characterized using a Geographic Information System (GIS) model that integrates and expands several existing resource assessments. We do a sensitivity analysis by altering one input parameter value like kitchen waste supply, transportation cost, and conversion rates to get the change in the size and location of the collection facility and biorefinery. Our study provides a comprehensive mathematical model which effectively brings together specific application feature especially in WCO-biodiesel supply chains.

1. INTRODUCTION

Recently, China has surpassed the U.S. and now is leading the world in energy consumption using more than 20% of the global energy[1]. The majority of consumption occurs in the transportation sector. There is an estimate that the transportation sector’s energy use increases 1.4% each year from 2008 to 2035[2]. With increasing oil consumption, it raises growing concerns towards global environment. To help alleviate these issues, China government is supporting the development of biofuel production as one of the ideal alternatives for transportation fuel. Because of the widespread concern over use of food crops for fuel production, biodiesel utilizing waste vegetable oil and cooking oil are very attractive, as the fuel feedstock already exists. Producing biodiesel waste products as feedstocks could have substantial environmental and economic benefits. Greenhouse gas emission and cumulative energy demand reductions on a life cycle basis can be achieved by biodiesel supply chain, such as a waste cooking oil to biodiesel production process[3]. At the same time, facilities utilizing cooking oil produce a viable fuel feedstock, waste oils are far less expensive than food-grade oils.
It’s estimated that China has produced considerable amount of WCO annually (about 4–8 million tons), and half of them could be collected for recycling[4]. However, WCO is not satisfactorily recycled for industrial use in the past years, as 40–60 percent is backflow to dining tables through various channels[5]. For this regard, Chinese government has highly supported the WCO-for-biodiesel industry and proposed that WCO should be the main feedstock of biodiesel in the document “Biodiesel industry development policy”. To facilitate the rapid expansion of biodiesel production and delivery in the next few decades, a sustainable supply chain system that ensures strong cost competitiveness, environmental benefits and reliability is crucial.

2. LITERATURE REVIEW
In 2010, the Energy Information Administration (EIA) reported U.S. transportation sector to be the country’s sole consumer of biodiesel, with a demand of 0.034 quadrillion Btu (3.56x1010 MJ), or only 0.4% of the total renewable energy consumed [6]. Then with the Renewable Fuel Standard (RFS) increasing the required consumption of all renewable fuels, including biodiesel, this percentage is expected to increase [7]. The transportation sector will likely continue to be the largest consumer of biodiesel because the infrastructure for vehicle biodiesel is well developed. Biodiesel is gaining importance due to its environmental and economic benefits Milano et al. [8] and Connolly et al. [9] reported the economic and environmental benefits of replacing fossil fuels with biodiesel.

In China, many scholars have pointed out the importance of promoting waste oil refining biofuel [10]. Zhang [11] and Zhang [12] have emphasized the necessity from supply chain or industry chain. On the optimization model, many authors have worked on it for the biodiesel supply chain. An et al. [13] develop an optimization model for a three level supply chain in a multi-period context that determines the biorefinery locations to minimize the total cost. Bowling et al. [14] present a model for a three level upstream network that aims to maximize the total system profit while determining the preprocessing and processing. Chen and Onal [15] propose a mixed integer nonlinear programming model that incorporates feedstock price, harvesting decisions, and biorefinery locations for profit maximization and develop an iterative heuristic procedure for its solution. Eksioglu et al.[16] present a MILP model which considers both the upstream and downstream decisions of biofuel supply chain. Kim [17] proposed two and multistage Mixed-Integer Linear Program (MILP) formulations to optimize the biodiesel supply chains. Xie [18] proposed a three-stage model with both economic and environmental objective. Zhang [19] a proposed a robust optimization model with three-level network considered the WCO suppliers, integrated biorefinery and demand zone as a model. Gokhan [20] consider the upstream midstream and downstream of ethanol supply chain then proposed a four stage stochastic model to optimize the biofuel supply chain, however, the model only have economic objective.

3. PROBLEM STATEMENT
This paper is based on using waste cooking oil to produce biodiesel as the background. We consider four levels facilities for biodiesel supply chain. They are (1) kitchen waste supplier, here is restaurant (2)WCO collection facilities, where the WCO is stored (3) Biodiesel refineries where WCO is converted to biodiesel (4)blending facility, like a gas station where is caused the demand of biodiesel. The ultimate goal of this paper is to minimize the integrated supply chain economic costs and carbon emission.

Based on the problem, two objective programming model is formulated as follows:
Objective1-Mimimization of the economic cost for the integrated supply chain system.

In the objective 1, the integrated supply chain optimization decision contains the kitchen waste collection from the supplier to the collection facility, biodiesel production at the biorefinery and the transportation decisions between the four facilities.
\[ \min F_1 = \sum_{t \in T} \left[ FTC(t) + BTC(t) \right] + \sum_{j \in J} \sum_{l \in L} f^{jt} Z_{jl} + \sum_{k \in K} \sum_{l \in L} f^{kl} Z_{kl} + \sum_{j \in J} \sum_{l \in L} c^{fr} q_{ijt} + \sum_{j \in J} \sum_{l \in L} c^{bfp} P_{kbt} + \sum_{l \in L} \sum_{t \in T} \left[ c^{fs} f_{jt} + \sum_{k \in K} c^{bs} S_{kbt} \right] \]

Where

\[ FTC = \sum_{j \in J} \sum_{l \in L} \left\{ c^{il} + \frac{c^{id}}{V} \right\} \times d_{jl} q_{ijt} \left( 1 - \alpha \right) + \sum_{j \in J} \sum_{l \in L} \left\{ c^{il} + \frac{c^{id}}{V} \right\} \times d_{jk} q_{ijt} \left( 1 - \alpha \right) \]

\[ BTC = \sum_{k \in K} \sum_{b \in B} \left\{ \frac{c^{eb}}{V} \times d_{sb} q_{kb} \right\} \]

Objective 2 - Minimization of the GHG emission for integrated supply chain system.

In objective 2, we consider the GHG emission in the process of WCO collecting, biodiesel production, and transportation. Transportation emission consists of two parts: being the emissions of WCO shipping from restaurant to the biorefineries and being the emissions of biodiesel shipping from biorefineries to the blending facilities.

\[ \min F_2 = \sum_{i \in I} \left[ E^{cr} + E^{br} + \sum_{j \in J} \sum_{l \in L} e^{jlt} q_{ijt} + \sum_{k \in K} \sum_{b \in B} e^{bfs} q_{kbt} \right] \]

Where:

\[ E^{cr} = \sum_{j \in J} \sum_{l \in L} \left\{ e^{jl} \times \frac{d_{jl}}{M^{vl,l}} \times d_{jl} q_{ijt} \left( 1 - \alpha \right) \right\} + \sum_{j \in J} \sum_{l \in L} \left\{ e^{jl} \times \frac{d_{jl}}{M^{vl,l}} \times d_{jl} q_{ijt} \left( 1 - \alpha \right) \right\} \]

\[ E^{br} = \sum_{k \in K} \sum_{b \in B} \left\{ \frac{e^{bl}}{M^{bl}} \times d_{sb} q_{kb} \right\} \]

Then, this paper uses the maximum efficiency solution to solve the two objectives optimization problem. That is the objective of Compromise Model:

Minimize \( F = \left[ \begin{array}{c} w_1 F_1 - F^{\alpha}_1 - F^{\beta}_1 \\ w_2 F_2 - F^{\alpha}_2 - F^{\beta}_2 \end{array} \right] \]

\( F^{\alpha}_1, F^{\beta}_1, F^{\alpha}_2, F^{\beta}_2 \) respectively represent the anti-optimal result of the \( F_1, F_2 \). The weight \( w_i \) is defined with the Analytic Hierarchy Process(AHP) method which is widely adopted by the international

Constraints Sets:

The constraints on supplier, collection facility, biorefineries, and the blending facility will be presented as follows.

Constraints on supplier:

\[ \sum_{j \in J} q_{ijt} \leq N_{a} \quad \forall i \in I, t \in T \]

Constraints on collection facility:

\[ \sum_{i \in I} q_{ijt} \leq \sum_{j \in J} M_{ijt}^{cr} Z_j \quad \forall j \in J, t \in T \]

\[ S_{j}^{t} \leq \sum_{i \in I} M_{ijt}^{cr} Z_j \quad \forall j \in J, t \in T \]

\[ \sum_{i \in I} q_{ijt} + (1 - \alpha)S_{j}^{t-1} = \sum_{k \in K} q_{ijk} + S_{j}^{t} \quad \forall j \in J, t \in T \]
Constraints on biorefineries:
\[
\sum_{t \in T} q_{jst} \leq \sum_{l \in L} M_{i}^{bb} Z_{sli} \quad \forall k \in K, t \in T
\]  
\[
S_{kt} \leq \sum_{t \in T} M_{i}^{bb} Z_{klt} \quad \forall k \in K, t \in T
\]  
\[
\mu \beta P_{k} \leq \sum_{t \in T} M_{i} Z_{klt} \quad \forall k \in K, t \in T
\]  
\[
\mu \beta P_{kt} \leq \sum_{t \in T} M_{i} Z_{klt} \quad \forall k \in K, t \in T
\]  
Constraints on blending facility:
\[
\sum_{b \in B} q_{b} \geq N_{jst} \quad \forall b \in B, t \in T
\]  
Integar and non-negativity constraints:
\[
\sum_{l \in L} Z_{klt} \leq 1 \quad \forall k \in K
\]  
\[
\sum_{l \in L} Y_{jlt} \leq 1 \quad \forall j \in J
\]  
\[
q_{jlt}, q_{jst}, q_{lb}, P_{k} \geq 0
\]

4. CASE STUDY
The compromise model has been applied to a case study of biodiesel supply chain in Jiangsu China. Jiangsu serves as a good case study for two primary reasons. First, the government of Jiangsu has been very positive to promote WCO harmless treatment and it is the one of the first pilot province for the biodiesel application. Second, because the economic development, Jiangsu has better advanced technology and professional expert in this field than other province, the WCO are anticipated to be ready for commercialization. The planning horizon is set between 2017 and 2027, which is consistent with the time frame when the adopted WCOs-to-biodiesel conversion technology is anticipated to be commercialized.

5. RESULTS AND DISCUSSION
Building on the base setting S1, for analysis, we generate four additional different settings by varying input parameters values. In S2, S3, S4 we alter one input parameter value while keeping the other parameters at their nominal values. The second setting (S2) alters kitchen waste supply 30% at the supply point. Lastly, we increase the conversion rate 8% in setting three (S3) and transportation costs 20% settings four (S4). All models were implemented and solved in MATLAB. Then, we present the results. Here, the meaning of some symbols are as follows: ![Large size biorefinery](#) ![Middle size biorefinery](#) ![Small size biorefinery](#) ![Large size collection facility](#) ![Middle size collection facility](#) ![Small size collection facility](#).

![Figure 1. S1 setting network analysis](#)
Figure 1 shows the collection facility and biodiesel locations for the base setting S1. In this case, there are a total of eleven open collection facilities: three large, five middle and three small. These eleven collection facilities almost cover the cities in Jiangsu province except for Suqian and Yangzhou. Combined with the map of supply, we can see the supply of kitchen waste in Suqian and Yangzhou is relatively small. There are more collection facilities open in the south of the province due to the existence of biodiesel demand in those cities as well as kitchen waste supplies.

Moreover, there are three large size biorefinery open at the south of the province to facilitate produce the biodiesel to meet the major demand in the south. In addition, there are one large size collection facility and a middle refinery open in North Jiangsu to achieve self-sufficient in the north.

![Figure 2. S2 setting network analysis](image)

In this setting (Figure 2), we observe the collection facilities and biorefineries both increase a lot. The collection facilities are from 11 in base setting to 17 in setting 2 to hold the inventory. The increased 6 facilities are respectively 3 large level, 2 middle level and 1 small level. Large collection facility are still mainly in the south where the demand and most of the supply are located. The increased 4 biorefineries are 1 large level 1 middle level and 1 small level. Biorefineries increase to adapt to the supply variability.

![Figure 3. S3 setting network analysis](image)

Since conversion rates are higher in this setting (Figure 3), more biodiesel is produced to satisfy most of the demand with available kitchen waste supply. Additional kitchen waste supply is obtained mostly from south, thus, due to the higher conversation rate the locations of 3 large biorefineries reduced 2 large and 1middle. Moreover, in the north the 2 middle biorefinery reduced to 1 middle level and 1 small level.

![Figure 4. S4 setting network analysis](image)

In S4 in which the unit transportation costs are higher, five biorefineries, 3 large level and two middle are opened similarly to S1 as showed in Figure 4. However, the collection facilities decrease from 11 in S1 to 9. The new collection facilities consist 3 large level, 5 middle level, 2 small level. The changed collection facilities are mainly happened in the north. This helps more economical to the the
transportation of kitchen to the biorefineries. With the increase in kitchen waste transportation cost, the role of collection facilities becomes more important, thus, the number of small collection facilities decrease and the large collection facilities have to spread more supplier so that they can have a more economical purpose.

6. CONCLUSIONS
This paper developed a new multi-objective, multistage optimization framework planning of biodiesel supply chain with supplements of waste cooking oil in seeking the best compromise solutions between the economic effectiveness and environmental purpose. The model was implemented in an illustrative case study of Jiangsu in China. In the model design process, this paper presents a deterministic multi-period network model in the upstream and downstream WCO-biodiesel supply chain. Our model simultaneously incorporates design and planning decisions and application specific system constraints such as time-dependent kitchen waste deterioration, locations of both collection facilities and biorefineries as well as their capacities and inventory decisions. In the optimization of biodiesel supply chain, the paper demonstrated the importance of integrating “environmental thinking” into the supply chain planning. Although there are other studies presenting similar models for biodiesel supply chains, our study provides a comprehensive mathematical model which effectively bring together specific application features especially in WCO-biodiesel supply chains.

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