An Optimization Model for a Thermochemical Biofuels Supply Network Design

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Abstract

This research focuses on the supply chain network design for the fast pyrolysis and hydroprocessing production pathway, utilizing corn stover as feedstock to produce gasoline and diesel fuel. A Mixed Integer Linear Programming (MILP) model is formulated to optimize the fast pyrolysis and hydroprocessing facility locations and capacities to minimize total system cost, including feedstock collecting cost, capital cost of facilities, and transportation costs. The economic feasibility of building a new biorefinery in Iowa is analyzed based on the optimal supply chain configuration and savings in bio-oil logistic costs to the centralized upgrading facility.

Keywords: Optimization Model, Thermochemical Biorefinery, Supply Chain Network, Fast Pyrolysis.

Introduction

Second generation biofuels are produced from non-food biomass, such as agricultural residues, and are less land- and water-intensive than first generation biofuels (Carriquiry et al., 2011). Cellulosic biofuel production pathways, such as cellulosic ethanol, and fast pyrolysis with hydroprocessing are expected to play an increasingly important role in fossil fuel displacement,

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national energy security, greenhouse gas reduction, and rural economic development (Lynd et al., 2009).

In 2007, the U.S. Environmental Protection Agency (EPA) established the revised Renewable Fuel Standard (RFS2) as a means of replacing domestic petroleum-based fuel consumption with biofuel consumption. The RFS2 mandates the U.S. consumption of 36 billion gallons per year (BGY) of biofuels by 2022. Of this volume, 16 BGY must come from cellulosic biofuels (2010). The cellulosic biofuel volume standard for 2012 is 10.45 million gallons per year (MGY) (EPA, 2011), which is only 0.06% of the total RFS2 mandate for 2022; thus, cellulosic biofuel has a long way to go to reach the EPA goal. Total logistic costs along the supply chain constitute 25% of the total fuel cost (Hess et al., 2007). Feedstock production and logistics constitute 35% of the total production costs of advanced biofuel (Aden et al., 2002; Phillips et al., 2007), and logistic costs associated with moving biomass from land to biorefinery can make up 50–75% of the feedstock costs (Grant et al., 2006). Collectively, the supply chain system activities of harvest, collection, storage, preprocessing, handling, and transportation, represent one of the largest challenges to the cellulosic biofuels industry. It is thus very important to investigate the supply chain design of the biofuel production systems as part of evaluation on their economic feasibility (Bai et al., 2011).

Thermochemical biofuel production pathways offer opportunities for rapid and efficient processing of diverse feedstock into fuel and chemicals (Adams et al., 2011; Brown, 2011; Haro et al., 2013). Fast pyrolysis is a thermochemical process that can be used to convert lignocellulosic biomass into three different products: bio-oil, biochar, and non-condensable gases (NCG) (Kauffman et al., 2011). Several previous studies report the costs of producing biobased hydrocarbons via fast pyrolysis and upgrading (Islam and Ani, 2000; Wright et al., 2010). Bio-oil

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is a viscous and corrosive liquid that must be upgraded prior to refining, which can occur either at a decentralized fast pyrolysis facility or at a centralized dedicated refinery. Upgrading can be accomplished either catalytically via fluid catalytic cracking or by reaction with hydrogen via hydroprocessing. Upgraded bio-oil undergoes a refining step in which it is split into separate hydrocarbon streams according to boiling range that are then blended into gasoline and diesel fuel.

Supply chain management is a relatively well-studied area, especially in the traditional manufacturing and service sectors. There is an emerging literature on supply chain design for the biofuel industry. The majority of the biofuel supply chain literature focuses on the deterministic decision making. Tsiakis et al. (2008) proposed a mixed integer linear programming (MILP) model for the design and operation of general supply chain networks. The model minimizes the total costs including infrastructure costs, production cost, material handling costs, and transportation costs. Ekşioğlu et al. (2009) proposed a model coordinating the long-term decisions of supply chain design, and the medium- and short-term decisions of logistics management of the biomass-to-biorefinery supply chain. Biomass-to-liquids supply chain design was studied by You et al. (2011) using a bicriterion MILP model. Optimal plant construction decisions are analyzed to study the trade-off of economic and environmental criteria. Hajibabai et al. (2013) presented an integrated mathematical model for biofuel supply chain design, minimizing total costs for facility construction, roadway capacity expansion and transportation. The authors consider multimodal transportation for biomass and biofuel shipments and also take into account the expansion of distribution infrastructure. Uncertainty is an important factor in the biofuel supply chain design, thus researchers started to incorporate the risks and uncertainties into the decision making. Chen et al. (2012) established a two-stage stochastic programming

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model for bioethanol supply chain system design considering uncertainties in feedstock supply and future demand. The authors also present a case study in California, optimal infrastructure layout and resource allocations are analyzed. Gebreslassie et al. (2012) proposed a bicriterion, multiperiod, stochastic MILP model dealing with biorefinery supply chains under uncertainties, minimizing the expected annual cost and financial risk. It is observed in the literature that the fuel product is mainly biobased ethanol which faces significant challenges due to the blending wall. Huang et al. (2010) developed a multistage modeling technique for strategic planning of bioethanol production system. A case study of multistage supply chain design in California was demonstrated, which shows the potential of bioenergy in improving energy sustainability. Kocoloski et al. (2011) discussed the impact of facility sizing and location on the cellulosic ethanol industry, and the infrastructure investment is modeled with a mixed integer program (MIP). Blending wall constraint is the major motivation to study the thermochemical production platform since the final products are gasoline and diesel equivalent hydrocarbons, which alleviate the constraint on blending.

This study investigates the supply chain design and configuration for a thermochemical production pathway with distributed processing facilities and centralized biorefinery. The MILP models formulated consider the entire supply chain of biofuel production, from biomass collection to final biofuel distribution. Both facility locations and capacities are optimized, which are essential to the biofuel supply chain network design. This is due to the high capital costs, longevity, and inflexibility to make changes for the biofuel supply network. The MILP models are then applied to a distributed fast pyrolysis facility and centralized biorefinery supply chain network for a case study in Iowa. In the case study, liquid transportation fuel is produced from corn stover, via decentralized fast pyrolysis with mild hydrotreating and centralized

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hydrocracking and refining. The economic feasibility of investing in a new centralized biorefinery in Iowa is analyzed by analyzing the cost savings to utilizing an existing petroleum refinery in Louisiana.

The rest of this paper is organized as follows: Methodology section presents two location-allocation models dealing with the two refinery scenarios (building one biorefinery in Iowa or utilizing an existing petroleum refinery in Louisiana). The problem statement, mathematical notations, and model formulation are introduced afterwards. The numerical examples are then illustrated in Numerical examples section with scenario descriptions, data sources, and the result analysis. The economic comparisons between the two scenarios are also illustrated. The paper concludes with a discussion of the results and a summary of managerial findings.

Methodology

In this section, a problem statement for the distributed biorefinery supply chain network design is presented, mathematical notations are introduced, and the MILP models are detailed.

Problem statement

A typical biofuel supply chain includes feedstock production, feedstock transportation, biofuel conversion, and biofuel distribution. Figure 1(a) provides a schematic of the fast pyrolysis and hydroprocessing pathway. The corn stover feedstock is first collected and shipped to the distributed fast pyrolysis facility where it is converted to raw bio-oil. The raw bio-oil is treated with hydrogen to remove impurities and reduce its oxygen content at the distributed fast pyrolysis processing sites. The distributed fast pyrolysis processing unit is illustrated by the components within the dashed box in Figure 1 (a). The hydrotreated bio-oil then undergoes hydrocracking (a reaction with hydrogen under more severe conditions than hydrotreating to

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depolymerize the high molecular weight compounds in the hydrotreated bio-oil) and refining (splitting of the bio-oil hydrocarbon fractions by molecular weight and blending to yield biobased gasoline and diesel fuel) to yield transportation fuels. The hydrocracking and refining is done at a centralized location to take advantages of economies of scale (Wright et al., 2008). A decision has to be made as to whether to utilize existing refining capacity in a non-optimal location (a refinery in Louisiana in the Iowa case study) or an optimally-located new biorefinery. The refinery decision implies a trade-off between the capital investment for the new biorefinery and the transportation costs to move the bio-oil between the distributed fast pyrolysis facilities and the existing refinery.

A supply chain network design framework is formulated to identify the optimal locations and capacities of fast pyrolysis and hydroprocessing facilities. Two modeling scenarios for the upgrading facility siting are considered: Scenario 1 assumes that the hydrotreated bio-oil is transported to an existing petroleum refinery in Louisiana for hydrocracking and refining, while scenario 2 assumes that a new biorefinery is built in Iowa. The mathematical model identifies the optimal location of the centralized biorefinery in scenario 2.

Mathematical notations

The mathematical notations utilized in the model are listed in Table 1 (superscripts are used to explain which scenario those notations are used in). Figure 1b summarizes the notations utilized in the model formulation.

Model formulation

A MILP model is developed to identify the optimal supply chain configurations to minimize the total system cost along the supply chain. Two scenarios have been analyzed based on the

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assumptions for the centralized upgrading and refining facility. In scenario 1, the upgrading and refining is taking place in an existing non-optimally located facility in Louisiana. In scenario 2, the centralized refining facility is optimally located in Iowa.

Scenario 1: Use existing refinery

The model for scenario 1 identifies the optimal locations and capacities for the distributed fast pyrolysis and hydrotreating facility network, and the hydrotreated bio-oil is hydrocracked and refined at an existing refinery.

The objective function is to minimize the total annual system cost, which includes biomass collection cost, biomass transportation cost, amortized fast pyrolysis facility capital cost, hydrotreated bio-oil shipping cost, and gasoline and diesel fuel distribution cost.

$$\min \zeta_1 = \sum_{i=1}^{N} \sum_{j=1}^{M} (BSC_{ij} + BCC_i) x_{ij} + \sum_{j=1}^{M} \sum_{l=1}^{L} FFC_l f_{jl} + \sum_{j=1}^{M} USC_j y_j + \sum_{k=1}^{K} GSC_k \, Dmn_k \qquad (1)$$

Notice that the gasoline and diesel fuel distribution cost (last term in objective function) is a constant since both the shipping amount and distance are parameters. Although it does not affect facility location and capacity decision-making, it is included to keep the consistency between of scenario 1 and 2.

The constraints include that (1a) the total biomass shipped from the biomass supplier does not exceed the supplier's total available biomass; (1b) the amount of hydrotreated bio-oil produced in a facility is based on the amount of biomass shipped to that facility and the conversion rate is based on experimental data; (1c) the total amount of biomass shipped to the fast pyrolysis facility does not exceed facility capacity; (1d) no more than one facility can be located at each candidate site; and (1e) the gasoline and diesel fuel produced meet the biofuel demand .

$$\sum_{j=1}^{M} x_{ij} \leq Spp_i, \forall i \quad \text{biomass availability} \quad (1a)$$

$$y_j = (1 - loss)\theta_1 \sum_{i=1}^{N} x_{ij}, \forall j \quad \text{biofuel conversion} \quad (1b)$$

$$(1 - loss)\sum_{i=1}^{N} x_{ij} \leq \sum_{l=1}^{L} f_{jl} C_l T, \forall j \quad \text{facility capacity} \quad (1c)$$

$$\sum_{l=1}^{L} f_{jl} \leq 1, \forall j \quad \text{one capacity level facility at each site} \quad (1d)$$

$$\theta_2 \sum_{j=1}^{M} y_j = \sum_{k=1}^{K} Dmn_k \quad \text{satisfaction of demand} \quad (1e)$$

$$x_{ij}, y_j \geq 0, f_{jl} \in \{0,1\}, \forall i, j, l, r \quad (1f)$$

Scenario 2: Build a new biorefinery

In scenario 2, in addition to optimizing the locations and capacities of the decentralized fast pyrolysis facilities (as in scenario 1), the goal is to optimize the integrated biofuel production network, including the location of the new centralized biorefinery.

The objective function in scenario 2 is also to minimize the total annual system cost. The difference is that instead of transporting the mildly hydrotreated bio-oil to an existing refinery site, the bio-oil is transported to the optimally located biorefinery for hydrocracking and refining. The annual cost reduction from scenario 1 to scenario 2 is to analyze the economic feasibility of building a centralized biorefinery.

$$\begin{aligned} \min \zeta_2 = \sum_{i=1}^{N}\sum_{j=1}^{M}(BSC_{ij} + BCC_i)x_{ij} + \sum_{j=1}^{M}\sum_{l=1}^{L} FFC_l f_{jl} + \sum_{j=1}^{M}\sum_{r=1}^{R} USC_{jr} y_{jr} \\ + \sum_{r=1}^{R}\sum_{k=1}^{K} GSC_{rk} z_{rk} \end{aligned} \quad (2)$$

The majority of the constraints are similar to those of scenario 1. Distinctions in the constraints include: (2e) hydrotreated bio-oil is shipped to an optimally located biorefinery; (2f) only one

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biorefinery is planned to cover the upgrading and refining need; (2g) conversion balance from hydrotreated bio-oil to transportation fuels; and (2h) the produced transportation fuels will satisfy fuel demand.

$\sum_{j=1}^{M} x_{ij} \leq Spp_i, \forall i$	biomass availability	(2a)
$\sum_{r=1}^{R} y_{jr} = (1 - loss)\theta_1 \sum_{i=1}^{N} x_{ij}, \forall j$	biofuel conversion	(2b)
$(1 - loss) \sum_{i=1}^{N} x_{ij} \leq \sum_{l=1}^{L} f_{jl} C_l T, \forall j$	facility capacity	(2c)
$\sum_{l=1}^{L} f_{jl} \leq 1, \forall j$	one capacity-level facility at each site	(2d)
$y_{jr} \leq M_r g_r, \forall j, r$	biorefinery capacity	(2e)
$\sum_{r=1}^{R} g_r = 1$	one biorefinery to build	(2f)
$\theta_2 \sum_{j=1}^{M} y_{jr} = \sum_{k=1}^{K} z_{rk}, \forall k$	transportation fuels conversion	(2g)
$\sum_{r=1}^{R} z_{rk} = Dmn_k, \forall r$	satisfaction of demand	(2h)
$x_{ij}, y_{jr} \geq 0, f_{jl}, g_r \in \{0,1\}, \forall i, j, l, r$		(2i)

It should be noted that the total annual costs for both scenarios should also include the conversion costs from biomass to hydrotreated bio-oil. Since both scenarios will satisfy the same total demands, the amount of biofuel produced will be the same. Therefore, the bio-oil conversion costs will be the same for both scenarios and thus will not impact the supply chain network decisions. The bio-oil conversion cost is not included in the objective function, but is rather incorporated into the scenarios' comparison.

Numerical examples

Iowa is chosen as the region of interest in the numerical example. Corn stover accounts for the major cellulosic biomass in Iowa (USDA/NASS). The goal of the biofuel supply chain design is

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to identify the locations and capacities for the distributed fast pyrolysis facilities in Iowa. Two scenarios are investigated regarding the centralized refinery location: (1) transporting the mildly hydrotreated bio-oil to the existing refinery in Louisiana for hydrocracking and refining; and (2) building a new biorefinery in Iowa to enable local refining of the mildly hydrotreated bio-oil.

Data sources

We consider each county of Iowa as a potential biomass (corn stover) supplier. The annual available weight of corn stover is estimated based on the corn yield considering the residue-to-grain ratio (Heid, 1984). The county level corn production data is from the National Agricultural Statistics Service (NASS). The National Resources Conservation Service (NRCS) Soil Quality Team suggests that excessive removal of residues, which perform many positive functions for soils in the agro-ecosystem, can harm soil quality (Andrews, 2006). Papendick et al. (1995) shows that a 30% removal rate results in 93% soil cover after residue harvest. In this study, we assume that the maximum biomass supply is 70% of total available corn stover. The county-level corn stover supply distribution is shown in Figure 2a. The stover collection cost is calculated based on the amount to be collected and machinery to be utilized. The collection methods differ due to the amount of stover collected at each county. Different regression equations are used for cost estimation based on the ranges of corn stover collection quantities (Graham et al., 2007). Biomass losses are incorporated for the collection and transportation process. It is assumed to be 5 wt% (weight percentage) in this study.

The main product for this production pathway is the transportation fuels. The gasoline demand is assumed to be proportional to the population of metropolitan statistical areas (MSAs). The total gasoline demand of Iowa is obtained from state-level gasoline consumption data provided

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by the Energy Information Administration (EIA) (DOE/EIA, 2011). The gasoline demand of the individual MSA in Iowa is shown in Figure 2b.

The candidate locations for the distributed fast pyrolysis facilities are at the county centroids. In scenario 2 where the centralized biorefinery site is to be determined, the candidate biorefinery locations are also assumed to be the county centroids in Iowa. Transportation distances for biomass, bio-oil and final transportation fuel are calculated using great circle distances (the shortest distance between any two locations on a sphere surface). The actual transportation distances are modified with circuity factors considering the difference in the transportation modes (e.g. 1.22 = truck circuity factor, 1.10 = oil pipe circuity factor) (1982).

Stover transported via truck incurs a distance fixed cost of $4.39/metric ton and a distance variable cost of $0.19/ton-mile (Searcy et al., 2007). The transportation cost of hydrotreated bio-oil via truck is assumed to be equal to the national average truck shipping cost of $0.26/ton-mile. The transportation cost of gasoline via pipeline is assumed to be equal to the national average oil pipeline cost of $0.027/ton-mile.

The distributed fast pyrolysis facility in this study converts corn stover to bio-oil via a fluidized bed reactor for the thermochemical conversion. In a hydrogen-purchase fast pyrolysis and upgrading scenario, conversion ratios are 0.63 for the bio-oil yield from biomass and 0.42 for the fuel yield from bio-oil (Wright et al., 2010). Unit conversion cost is estimated with total annual operating cost of a hydrogen-purchase fast pyrolysis and upgrading scenario at approximately $1.18/gallon (2010).

In the numerical examples, we consider four available capacity levels: 400, 1000, 1500, and 2000 metric ton/day. The capacity levels are represented by the amount of dry basis biomass a facility is capable of processing per day. The capital cost of the facility is the total project

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investment minus working capital and land. The capital cost of the fast pyrolysis facility with a capacity of 2,000 metric ton/day is $200 million (assuming a hydrogen purchase plant) (Wright et al., 2010), and the capital costs for other capacity levels are estimated using a facility capital scaling factor of 0.6:

$$\left(\frac{Capacity_1}{Capacity_2}\right)^{0.6} = \frac{Capital\ Cost_1}{Capital\ Cost_2}.$$

The objectives of both scenarios models are the minimization of the annual total system cost. Therefore, an amortized facility capital cost is calculated for a fast pyrolysis facility with a 20-year life and an interest rate of 10%.

Numerical results

Numerical results and modeling analysis for both refinery scenarios are presented in this section.

Scenario 1: Use an existing refinery in Louisiana

Scenario 1 determines the optimal decentralized fast pyrolysis facility locations and capacities. The mildly-hydrotreated bio-oil is hydrocracked and refined in an existing refinery in Louisiana.

The optimal distributed fast pyrolysis facility locations are illustrated in Figure 3 (background is the map of spatial distribution of corn stover in Iowa). Different shaped points mark the facility locations of different capacity levels: a pentagon represents a 400 metric ton/day facility, a triangle represents a 1000 metric ton/day facility, a square represents a 1500 metric ton/day facility, and a circle represents a 2000 metric ton/day facility. The shaded counties provide biomass to the fast pyrolysis facilities and all biomass is from the same county as the location of the past pyrolysis facility. The stars are the centroids of the MSAs. The sizes of the stars illustrate the magnitudes of the fuel demand from the MSAs, which are based on MSA-level gasoline demand data (shown in Figure 2b). The predetermined refinery location is in Louisiana.

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The numbers of facilities of each capacity level are:

400 metric ton/day	1000 metric ton/day	1500 metric ton/day	2000 metric ton/day
2	17	9	7

In this scenario, the optimal value of the total annual production cost (excluding the bio-oil conversion costs) is $2.5 billion. Itemized costs are listed in Table 2.

Scenario 2: Build a new biorefinery in Iowa

Scenario 2 determines the optimal decentralized fast pyrolysis facility locations and capacities. It also determines the location of the new biorefinery in Iowa.

Figure 4 (background is the map of spatial distribution of corn stover in Iowa) shows the supply chain network configuration for scenario 2. Different shapes are used to mark locations of different capacity facilities (pentagon – 400 metric ton/day, triangle – 1000 metric ton/day, square – 1500 metric ton/day, circle – 2000 metric ton/day), and the cross-shaded county is chosen to build the centralized biorefinery. Feedstock transported from counties outside of the facility-located county is illustrated with arrows.

The numbers of facilities of each capacity level are:

400 metric ton/day	1000 metric ton/day	1500 metric ton/day	2000 metric ton/day
0	0	0	18

In this scenario, the optimal annual total production cost (excluding the bio-oil conversion costs) is $880 million. Itemized costs are listed in Table 3.

Analysis and discussion of results

a) Comparison between two scenarios

In Numerical results section, the computational results of the biofuel supply chain network design for the two modeling scenarios are presented. Both models use MILP formulation to identify optimal fast pyrolysis facility locations and capacities based on minimizing total annual

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costs along the supply chain. In scenario 1, an existing petroleum refinery in Louisiana is chosen to hydrocrack and refine hydrotreated bio-oil to produce liquid transportation fuels. In scenario 2, the supply chain network design model identifies the optimal location of a new biorefinery in Iowa for the purpose of bio-oil hydrocracking and refining.

From Figure 3 and Figure 4, it should be noted that feedstock is primarily from the county where the facilities are built which reduces the transportation costs. In scenario 2, all facilities employ the highest available capacity level of 2000 metric ton/day, because a larger capacity facility is more cost-effective due to the facility capital scaling factor (the economies of scale). Though this still holds for scenario 1, some smaller facilities are also built to balance the facility capital cost and corn stover transportation cost.

It is also demonstrated in Figure 3 and Figure 4 that optimal facility locations tend to be closer to the refinery in scenario 1 and biorefinery in scenario 2. In scenario 1, the optimal facility locations are primarily in the southern part of Iowa. However, the mid-southern counties are not chosen to build a fast pyrolysis facility, nor are they chosen as feedstock supply locations. This is because of the low biomass availability of those counties. Fast pyrolysis facilities built in them will necessarily incur high biomass shipping costs. Therefore, the supply chain network design model demonstrates the capability of managing the trade-off of biomass and bio-oil transportation costs. In scenario 2, both the fast pyrolysis facilities and biorefinery are optimally located in the northern counties due to high feedstock availability in northern Iowa. This reduces both the distance of stover and bio-oil shipping and thus the total production cost. Figure 5 includes a bar chart for the comparison of the itemized costs for scenarios 1 and 2. In Table 4, the itemized costs, total production cost, and unit cost per gallon of liquid fuel for both scenarios are illustrated.

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The fast pyrolysis conversion costs are not included in the objective function in the model formulation. This is because the facilities will produce the same amount of biofuel for both scenarios; therefore, the fast pyrolysis conversion operating costs will be the same and will not affect the location and capacity decisions. In the total production cost analysis, the fast pyrolysis conversion operating cost is assumed to be $1.18/gallon (Wright et al., 2010). Both Figure 5 and Table 4 show that total transportation cost accounts for a much larger proportion of total annual cost in scenario 1 than in scenario 2. The cost difference between the two scenarios is primarily due to the shipping costs of both the hydrotreated bio-oil and the final biofuel products. This is because of the difference in bio-oil and biofuels transportation distances. The bio-oil and biofuel transportation distances for both scenarios are detailed below.

	Scenario 1	Scenario 2
Average hydrotreated bio-oil shipping distance (mile)	740.2	55.6
Average gasoline and diesel fuel shipping distance (mile)	759.7	145.0

Since the difference between the two scenarios lies in whether to use an existing petroleum refinery or use a new-built biorefinery at a preferable location for hydrotreated bio-oil refining, the difference between the optimal objective values of the two scenarios indicates a threshold of annual investment in the new-built biorefinery. In the case study, the annual reduction of $1.62 billion (calculated from Table 4) could justify the amortized capital cost of a 30-year biorefinery with $15.3 billion total capital cost, which shows the economic potential of building a new biorefinery in Iowa rather than shipping hydrotreated bio-oil to an existing refinery.

b) Sensitivity on biomass availability

To investigate the sensitivity of the biomass availability to the supply chain network design, we examine three corn stover availability scenarios. This analysis is motivated by the potential

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variation in stover availability due to uncertainty caused by weather, pests, etc. Different total annual costs considering stover supply availability are listed below.

	Scenario 1	Scenario 2
80% corn stover availability	$2,520,000,000	$893,000,000
100% corn stover availability	$2,506,000,000	$880,000,000
120% corn stover availability	$2,499,000,000	$872,000,000

The fast pyrolysis facility locations and capacities remain unchanged. However, the biomass flows change with corn stover availability. Increased stover availability provides higher flexibility in feedstock source choices, consequently reducing total system cost, while lower corn stover availability increases total cost. The change in the total cost is not very significant, which validates the robustness of the proposed biofuel supply chain design framework.

c) Alternative biorefinery location

In scenario 2, the centralized biorefinery location is an important decision for stakeholders. We have presented the results when the biorefinery is optimally located in Iowa. In this section, the impact of the Iowa biorefinery location is investigated. The authors study the pessimistic scenario where the worst location is selected for the Iowa biorefinery. This location is the one that obtains the highest annual system costs among all candidate biorefinery locations. The supply chain configuration result is shown in Figure 6 (background is the map of spatial distribution of corn stover in Iowa). The cost comparison between the optimal case and the pessimistic case is included in Table 5. As shown in Figure 6, the distributed fast pyrolysis facility locations are highly related to biorefinery location. With the biorefinery poorly located, fast pyrolysis facilities are chosen to balance feedstock availability and hydroprocessed bio-oil shipping distances. Consequently, logistic costs increase significantly. Some facilities have smaller capacities because they are located in counties with insufficient biomass supplies, and this causes additional facility capital cost, due to the increase in the number of facilities to satisfy all the demand. It can be seen from Table 5 that the optimally located biorefinery can significantly reduce total annual cost, especially the shipping cost.

Conclusion

Supply chain network design and optimization are essential to the successful deployment of advanced biofuel production. This study investigates a biofuel supply chain network design for pathways with distributed bio-oil production and centralized upgrading operations. It demonstrates that facility location and capacity decisions from this supply chain optimization framework can be effectively applied to the biofuel industry and significantly improve supply chain network performance, thus reducing total system costs. Biomass feedstock sourcing and biofuel distribution planning decisions are studied to provide managerial insights for investment decision making.

This study identifies the optimal facility locations and capacities for the production of gasoline and diesel fuel from corn stover via fast pyrolysis and hydroprocessing. Facility location and capacity decisions have a direct impact on costs along the supply chain, including feedstock transportation cost, biofuel production cost, and biofuel distribution costs. The numerical results in the case study demonstrate that transportation/logistic costs contribute significantly to total production cost.

The economic feasibility of a fast pyrolysis and hydroprocessing facility is maximized when transportation costs are reduced via the optimization of facility locations and capacities. This is true for both modeling scenarios for the bio-oil upgrading and refining facility. In scenario 2, locating a biorefinery in Iowa has the advantage of reducing the shipping costs of the intermediate hydrotreated bio-oil and the final fuel product. Building a biorefinery in Iowa could

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reduce the unit cost of gasoline from $3.31 to $1.93 per gallon. The total cost reduction per year, $1.6 billion, demonstrates the potential economic feasibility of building a new biorefinery in Iowa.

In summary, Mixed Integer Linear Programing (MILP) models are formulated to analyze facility location and capacity decisions for the production of gasoline and diesel fuel. The pathway under investigation is utilizing corn stover as the feedstock, with distributed fast pyrolysis and mild hydrotreating, and centralized hydrocracking and refining to produce biofuel. The economic feasibility of building a new biorefinery in Iowa is analyzed by comparing annual system costs between using an existing refinery in Louisiana and investing in a new biorefinery in Iowa. It should be noted that the optimization models provide the flexibility to adaptively analyze biofuel supply chain design problems at various scales, ranging from state level planning to national and international energy supply network design. On the other hand, this study is subject to a number of limitations. First, we assume the planning and construction of all the facilities happen in one stage, which may not be realistic. Sequential facility siting and sizing problems provide a future research direction. Second, operational planning and scheduling within the facilities are not considered in this framework. Last, the models in this study are deterministic. Additional research is needed to consider uncertainties along the biofuel supply chain, such as for feedstock quantities, feedstock price, biofuel demand, and market prices.

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Table 1 Sets, Parameters, and Decision Variables

Sets		
$\boldsymbol{i^{1,2}}$	$1,2,\ldots,N$	Biomass supply locations
$\boldsymbol{j^{1,2}}$	$1,2,\ldots,M$	Candidate facility locations
$\boldsymbol{k^{1,2}}$	$1,2,\ldots,K$	Gasoline and diesel fuel demand locations
$\boldsymbol{l^{1,2}}$	$1,2,\ldots,L$	Allowed fast pyrolysis facility capacity levels
$\boldsymbol{r^{2}}$	$1,2,\ldots,R$	Candidate biorefinery locations
Parameters		
$\boldsymbol{Spp_i}^{1,2}$	$dry\ ton$	Total biomass supply of biomass supplier i
$\boldsymbol{Dmn_k}^{1,2}$	$dry\ ton$	Total gasoline demand of gasoline demand location k
$\boldsymbol{C_l}^{1,2}$	ton/day	Capacity of fast pyrolysis facility at level l
$\boldsymbol{\theta_1}^{1,2}$		Conversion ratio, metric ton of upgraded bio-oil per dry metric ton of biomass
$\boldsymbol{\theta_2}^{1,2}$		Conversion ratio, metric ton of gasoline per metric ton of upgraded bio-oil
$\boldsymbol{D_{i,j}}^{1,2}$	$miles$	The distance from supply location i to candidate facility location j
$\boldsymbol{D_j}^{1}$	$miles$	The distance from candidate facility location j to fixed refinery
$\boldsymbol{D_{j,r}}^{2}$	$miles$	The distance from candidate facility location j to candidate biorefinery location r
$\boldsymbol{D_k}^{1}$	$miles$	The distance from fixed refinery location to gasoline demand location k
$\boldsymbol{D_{r,k}}^{2}$	$miles$	The distance from candidate biorefinery location r to gasoline demand location k
$\boldsymbol{\tau_t}^{1,2}$	$const$	Circuity factor for truck
$\boldsymbol{\tau_p}^{1,2}$	$const$	Circuity factor for pipeline
$\boldsymbol{T^{1,2}}$	day	Number of facility operating days per year
$\boldsymbol{BCC_i}^{1,2}$	$\$/ton$	Biomass collecting cost of supply location i
$\boldsymbol{loss^{1,2}}$		Loss factor, the weight percentage loss of biomass during collection and transportation
$\boldsymbol{F_t^{B}}^{1,2}$	$\$/ton$	Fixed cost for biomass shipping using truck
$\boldsymbol{V_t^{B}}^{1,2}$	$\$/ton-mile$	Variable cost for biomass shipping using truck
$\boldsymbol{BSC_{i,j}}^{1,2}$	$\$/ton$	Biomass shipping cost from supply location i to candidate facility location j $BSC_{ij} = F_t^B + V_t^B \times \tau_t \times D_{ij}$
$\boldsymbol{V_t^{U}}^{1,2}$	$\$/ton-mile$	Variable cost for hydrotreated bio-oil shipping using truck
$\boldsymbol{USC_j}^{1}$	$\$/ton$	Hydrotreated bio-oil shipping cost from candidate facility location j to fixed refinery $RSC_j = V_t^U \times \tau_t \times D_j$
$\boldsymbol{USC_{j,r}}^{2}$	$\$/ton$	Hydrotreated bio-oil shipping cost from candidate facility location j to candidate biorefinery location r $RSC_{jr} = V_t^U \times \tau_t \times D_{jr}$

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$V_p^{G\,1,2}$	$\$/ton-mile$	Variable cost for biomass shipping using truck
$GSC_k{}^{1}$	$\$/ton$	Biomass shipping cost from fixed refinery location to gasoline demand location k $GSC_k = V_p^G \times \tau_p \times D_k$
$GSC_{r,k}{}^{2}$	$\$/ton$	Biomass shipping cost from candidate biorefinery location r to gasoline demand location k $GSC_{r,k} = V_p^G \times \tau_p \times D_{r,k}$
$FFC_l{}^{1,2}$	\$	Fixed facility cost for capacity level l
$Cap_l{}^{1,2}$	ton/y	Leveled facility capacity
$Conv^{1,2}$	$\$/gal$	Conversion cost per gallon gasoline
$M_r{}^{2}$	gal/y	Biorefinery capacity
Decision Variables		
$\zeta^{1,2}$	\$	Total annual production cost excluding conversion cost
$x_{i,j}{}^{1,2}$	ton	Amount of biomass transport from supply location i to candidate facility location j
$y_j{}^{1}$	gal	Amount of hydrotreated bio-oil transport from candidate facility location j to fixed refinery
$y_{j,r}{}^{2}$	gal	Amount of hydrotreated bio-oil transport from candidate facility location j to candidate biorefinery location r
$z_{rk}{}^{2}$	gal	Amount of gasoline and diesel fuel transport from biorefinery location r to demand location k
$f_{j,l}{}^{1,2}$	$binary$	If a fast pyrolysis facility of capacity level l exists in candidate facility location j
$g_r{}^{2}$	$binary$	If a biorefinery exists in candidate biorefinery location r

[1] Parameters (or variables) for modeling scenario 1: utilizing existing refinery

[2] Parameters (or variables) for modeling scenario 2: building a new biorefinery at an optimal location

Table 2 Itemized Costs and Percentage of Total Annual Cost for Scenario 1

Corn stover collecting cost	$357,000,000	14.2%
Fast pyrolysis facility capital cost	$563,000,000	22.5%
Corn stover shipping cost	$56,000,000	2.2%
Hydrotreated bio-oil shipping cost	$1,464,000,000	58.4%
Gasoline and diesel fuel shipping cost	$66,000,000	2.6%
Total (excluding conversion cost)	$2,506,000,000	100.0%
Total (including conversion cost)	$3,892,000,000	

Table 3 Itemized Costs and Percentage of Total Annual Cost for Scenario 2 (excluding the capital cost for the centralized biorefinery)

Corn stover collecting cost	$311,000,000	35.3%
Fast pyrolysis facility capital cost	$382,000,000	43.4%
Corn stover shipping cost	$64,000,000	7.3%
Hydrotreated bio-oil shipping cost	$110,000,000	12.5%
Gasoline and diesel fuel shipping cost	$13,000,000	1.5%
Total (excluding conversion cost)	$880,000,000	100.0%
Total (including conversion cost)	$2,266,000,000	

Table 4 Annual Itemized Costs Comparison between Scenario 1 and 2

	Scenario 1	Scenario 2
Corn stover collecting cost	$357,000,000	$311,000,000
Fast pyrolysis facility capital cost	$563,000,000	$382,000,000
Corn stover shipping cost	$56,000,000	$64,000,000
Hydrotreated bio-oil shipping cost	$1,464,000,000	$110,000,000
Gasoline and diesel fuel shipping cost	$66,000,000	$13,000,000
Total	$2,506,000,000	$880,000,000
Cost per gallon gasoline and diesel fuel	$2.13	$0.75
Cost per gallon gasoline and diesel fuel (with conversion cost)	$3.31	$1.93

Table 5 Itemized Costs Comparison between Optimal Biorefinery Case and Pessimistic Case

	Optimal Case	Pessimistic Case
Corn stover collecting cost	$311,000,000	$342,000,000
Facility capital cost	$382,000,000	$411,000,000
Corn stover shipping cost	$64,000,000	$68,000,000
Hydrotreated bio-oil shipping cost	$110,000,000	$216,000,000
Gasoline and diesel fuel shipping cost	$13,000,000	$16,000,000
Total	$880,000,000	$1,053,000,000

List of figure captions

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